CONPLAN: CONSTRUCTION PLANNING AND BUILDABILITY EVALUATION IN AN INTEGRATED AND INTELLIGENT CONSTRUCTION ENVIRONMENT

Zainuddin Hassan

T.I.M.E Research Institute
Department of Surveying
University of Salford, Salford, UK

Submitted in Partial Fulfilment for the Degree of
Doctor of Philosophy, March, 1997

LIST OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

ACKNOWLEDGEMENTS

I would like to take this opportunity to extend my special thank to my supervisor Prof. Mustafa Alshawi for giving invaluable and continous support, guidance and assistance during my study and the preparation of this thesis. Special thanks are also extended to all AIC 's group, Dr. Ghassan Aouad, Dr. Ihsan Faraj, Dr. Jason Underwood and other members, for their interesting and lifely debates and suggestions of improvements during this study.

I am also grafeful in general to all staff in the Surveying Department, especially Dr. John Hinks, Ms. Sheila Walker and Mrs. Lynn Williamson for their assistance. I would also like to thank to all my friends in the department, especially Che Wan Fadhil and Jamil Sulaiman for helping with the prototype.

My gratitude is also due to SIRIM and the Malaysian's government for providing the sponshorship.

Finally, my parents, wife and children deserve the greatest thank for being very understanding and supportive throughout the years, while living and studying in this country.

LIST OF ABBREVIATIONS

Abbreviations	Meaning
AEC	Architecture, Engineering and Construction
AI	Artificial Intelligence
AIC	Automation and Integration in Construction
ASCII	American Standard Code for Information Interchange
BPM	Building Product Model
BCCM	Building Construction Core Model
CAD	Computer Aided Design
CIC	Computer Integrated Construction
CII	Construction Industry Institute
CIRIA	Construction Industry Research and Information Association
COMBINE	Computer Models for the Building Industry in Europe
CPM	Critical Path Method
DBMS	Data Base Management System
DDE	Dynamic Data Exchange
DXF	Data eXchange Format (CAD system)
ER	Entity Relationship
IBPM	Integrated Building Process Model
ICON	Integration of Information for CONstruction
IGES	Initial Graphical Exchange Specification
IRMA	Information Reference Model for AEC
ISO	International Standard Organisation
ICE	Integrated Construction Environment
JSD	Jackson System Development
LISP	High level programming language for AI
NEDO	National Economic Development Office
NIAM	Nijssen's Information Analysis Method
OFD	Object Flow Diagram
ORD	Object Relationship Diagram
PGES	Product Data Exchange Specification

PERT	Project Evaluation and Review Technique
PROLOG	Programming in Logic
SADT	Strutured Analysis and Design Technique
SASD	Structured Analysis and System Design
SSADM	Structured System Analysis and Design Methodology
STEP	STandard for Exchange of Product Data
KBS	Knowledge Base Systems
RDBMS	Relational Data Base Management Systems
RIBA	Royal Institute of British Architects
VE	Virtual Environment
VR	Virtual Reality

ABSTRACT

The lack of a buildability evaluation at the design stage coupled with the separation of the design and construction processes have been acknowledged to cause buildability problems on site. Normally, designers view of their task, is to develop a masterpiece which satisfies the functional requirements of a project while constructors consider their task as construction works, which need to be completed at the lowest price. No significant efforts have been made to bring the design and construction processes together to facilitate the integration of information for the improvement of the overall project performance.

This study proposes an integrated framework for construction planning which is capable of exchanging information with other construction disciplines and generating planning information in an integrated construction environment. Planning data and processes were first modelled using object oriented analysis methodology, i.e. Martin (1993), where the emphasis was placed on both the data and its behaviour. This development was carried out within a general integrated framework which facilitates the integration between the various construction application across the project life cycle. The developed models highlight the importance and the role of the planning process which is vital in providing relevant information to other disciplines.

Moreover, the study proposes a quantitative approach for a buildability evaluation based on the information available within the integrated environment. It evaluates the design solutions from the construction view, as outlined in the

construction plan. The qualitative principles of buildability improvements were adopted to formalise this approach. A combination of weightings and scores were assigned to building elements to reflect their buildability factors.

The developed data and process models, were implemented in an object oriented environment as part of a single integrated construction environment SPACE (Simultaneous Prototyping for An Integrated Construction Environment) where CONPLAN (Intelligent CONstruction PLANning for design rationalisation) is one of the SPACE modules. CONPLAN automatically generates the construction planning information and the buildability reports. The former can be dynamically accessed either through a planning package or visualised in a virtual space using a virtual reality package. The buildability reports can be either displayed in a textual or graphical format.

Chapter 1
Introduction

1.0 Introduction

The construction industry is profoundly recognised as being a fragmented industry (Howard *et al.,* 1989). The industry is different to any other industry by its size, uniqueness of the product, required various professionals, easily influenced by environment etc. No two projects are identical and site characteristics vary extensively (Seeley, 1984). The construction process has also increasingly been getting more complex by the availability and usability of various kinds of building materials, the new needs of construction technology, the wide range of building systems, the availability of new construction plant and machinery, the variety of professionals involved, as well as the sophisticated needs from the client, for the facility (Carrara *et al.*, 1991; Eastman, 1991). Due to the special characteristics of the construction industry compared to other industries, the encountered management problems in the design development and the construction process are complex and enormous.

The problems encountered in the production of a facility in the construction industry can be divided into two categories, internal and external. The internal problems range from developing optimum design solutions, choosing the right construction technology, selecting the construction process and procurement system, getting the right quality and cost, establishing the communication, organising, site management, etc. The external problems include the influence of the environmental variables such as political influences, legal restrictions and agreements, etc. (Bennett, 1985; Eastman, 1991; McDermott, 1994). Based on these facts, the development of a facility demands a great deal of knowledge and collaborative effort from various project participants e.g. the government bodies, a wide range of designers, multiple level and types of contractors, various sources of suppliers, and different types of skilled workers through out the project life cycle. To overcome the complexity of managing the construction processes, most clients of the construction industry have only to rely heavily on the skill of the designers, for assessing their needs, and the value of the solutions being proposed.

In practice, design and construction processes are normally carried out in a sequential manner. This approach has produced various advantages for the construction industry since 1805 (Dunican, 1984). It allows the various parties in the project to compete and provide the best results for the project while defending and upholding their rights and duties within their respective disciplines (Griffith, 1986). Although the separation of design and construction allows the construction processes to be managed systematically between the various stages and disciplines, the industry is still being criticised for poor performance, being under productive, lack of competitiveness, and consuming longer product development time.

Compared to the manufacturing industry, the construction industry has also been criticised for not improving their approach in developing and delivering the facilities to the clients. Examples shown in the manufacturing industry that combine the product design, process design, and design for manufacturability into a single step (Yu *et al.,*1993, Savindo & Medeiros, 1990), which brought major advantages to a product development, such as reducing the product development time, increasing its quality and lowering the production cost, has overwhelmed the construction industry (Tatum, 1987).

Various studies have revealed that since 1950, the construction industry has realised the important of analysing design for construction implications, if the production work on site is to be effectively performed (Gray,1986). The recommended solutions provided by the studies revealed that the separation of the design and construction processes, is the major factor responsible for contributing to the various problems in the construction projects. To overcome this inherent problems from the separation of design and construction, a concept known as buildability is established and 'marketed' to the industry (Illingworth, 1984; CIRIA, 1983; NEDO, 1975; Griffith, 1985; Gray, 1983; Moore, 1996). By using the buildability concept as a means to improve the construction industry, many ideas have been put forward by various researchers to remove the disadvantages of separating the design and construction process (Illingworth, 1983; CIRIA, 1983; CII, 1986; Tatum, 1987).

Besides producing general guidelines for the construction industry for reducing the problems, among the major findings suggested was to incorporate the contractor's views on construction at the design stage (Illingworth; 1984, NEDO; 1975). Although the idea was principally agreed as an ideal way of solving the buildability problems, however. in reality. the approach has failed to achieve its objectives. Luiten and Tolman (1992) added that

> "Designers are also often not really (financially) concerned with the construction process, because it is performed by other companies."

Many people in the professional teams especially the designers, also dislike the idea of the contractor questioning what they have designed or detailed. Further more, there was no significant effort made to encourage the co-operation of the design and the construction teams, contrarily, it was found that the approach was often actively discouraged (Illingworth, 1984; Coombs, 1983). With this unfortunate practice unlike the manufacturing industry. the client, consequently, is hindered from obtaining the best possible value for money in terms of the efficiency, to which the design and construction of the building are to be operated (Griffith, 1984: Underwood, 1995).

Since then, little progress of any kind has been made to improve the situation described earlier, not until 1979-80, when the Construction Industry Research Information Association (CIRIA) made an effort to call contractors to find out what they regarded as the main problem of buildability (Griffith, 1985). The move made by CIRIA (1983) has established clear evidence that the contractor's practical skills could provide a benefit to the construction industry, if only they could be incorporated in the design. Different procurement systems are introduced later in the attempt to reduce the buildability problems, such as design-build. construction management, etc. However, the required construction process knowledge is still rarely available to the designers when they are working on a project (Fisher, 1993; Alshawi & Underwood, 1996). Until now the question of how the buildability should be effectively implemented and analysed still remains to be further investigated and manifested.

1.2 The research background

Projects development in the construction industry evolves through many stages. Each stage of the project life cycle contains various processes by which their output provide the input for the following stage. The R.I.B.A Plan of Work describes briefly the various stages (R.I.B.A.,1980) for a project life cycle. For each stage of the project life cycle, the contained processes are executed by a specific profession i.e. designers, contractor, facility managers, etc.

Between the briefing and the construction stage, designers have the full responsibility to produce a design solution which meets the clients requirements, is economic to construct, and operable. At this stage, the design team has a large influence on the implications of buildability and cost on the project. As the stages sequentially move from design to construction, till the end of the construction work. the influence of the designers to control the cost of the project, will progressively become insignificant. Contrarily, if any changes are made by the designer on the design during the progress of the construction work, the result will be significant since the project cost will be indiscreetly increased, caused by the repercussions on other parts of the design (Crawshaw, 1976).

In practice, the designers are required to have a complete understanding of the fundamental aspects of the user requirements for the project, besides the ability to compare the ultimate cost consequences of the construction work from various other alternatives solutions (Allsopp, 1983; Coombs, 1983). These experts are also required to tackle all the problems in the design to meet the clients needs, such as, the feasibility of the project, design management, cost management, project execution, procurement and construction (Baxter, 1983). In general, they are expected to provide design solutions where different components of a facility capable of interacting with each other, within the ways the facility is to be used, and within the defined methods of construction costs, running cost and operating cost (Steve, 1983). These are essential to achieve an economical and operable design solution for the project besides avoiding the client paying undesirable costs from a complex and inappropriate design solution during construction stage.

Based on the range of essential requirements of a project, few designers can be expert in all facets of the project life cycle; it is obvious that the design team would be comprised of a variety of expertise i.e. from costing, services, structural, geology, material, building regulations and construction. Even though various parties in the design team would give their utmost professional recommendation to get the best performance or functional solution into their design and besides the quantity surveyors (measurers) providing the elemental cost analysis, the design team is still lacking, and has very minimum construction process knowledge to extend their analysis to evaluate the impacts of their design on the construction works, especially when the project is a new design (William, 1983; Fisher 1993).

Since the process of design and construction is performed separately by different parties at different stages of project life cycle, the various aspects of buildability would not be easily detected by the designers, in the design solution, unless they can extend their knowledge and imagination to see the implication of its design to the construction processes. The separation of the design and construction process in the project life cycle clearly obstructs the advantages of utilising the construction process knowledge held by the contractor which would normally be exercised when they formulate the construction methods and plan (Luiten & Tolman, 1992; Fisher *et al.*, 1995).

Some of the implications that contribute to buildability, which are rooted in the design solution, which would normally be difficult for the designers to contemplate are, complexity of the sequencing activity between various trades, constraints in handling various building materials imposed by site restrictions, the impact of different construction methods to the construction process, availability of resources (labour, skill worker. plant) in the area, utilisation of plant, economic construction methods and the impact of uncertainty for making decision during construction planning, due to absence of relevant information (Leon, 1971; Bennett & Ormerod, 1984; Gray, 1983; Illingworth, 1984; Mansfield, 1983). Lack of this knowledge during design, will obviously subject the design to buildability/constructability problems and the objective to provide efficient and economical assembly of the design components to form a facility could not be realised (Paulson. 1976; Gray, 1983; Fisher, 1991; CIRIA, 1983).

Unlike the manufacturing industry, it's a normal practice in a project life cycle that the construction process knowledge owned by the contractor is only used to provide outlines (construction plan and construction methods) on how the contractor constructs a given design, rather than advising or solving a design problem related to buildability. Various researchers agreed that if the construction information produced by the contractor from the development of the construction plan (i.e. construction activities, construction methods, cost, time, etc.) are available to the designers at the stage of design. the designer would be able to use this knowledge to obtain optimum design solutions by considering design as well as construct (Illingworth, 1984.; Griffith, 1985; Gray, 1986, Luiten & Tolman, 1992: Fisher *et al.*, 1995)

Since information technology has been increasingly used to improve the co-operative work and the information sharing between various designers. constructors and suppliers, this technology could also be used to capture the constructors knowledge on formulating the construction activities, methods and plans to evaluate the buildability of the project. The availability of powerful computer hardware and the software applications such as graphical applications, estimating packages, structural design packages, project planning packages, object oriented knowledge base systems or expert system shell, etc., provide a great opportunity to be used to identify and partially solve the inherent problem of buildability in the construction industry.

Since single environment tools of applications could incorporate the design and construction process knowledge from various project participants, an analysis tool could be developed to assist designers to obtain the optimum buildable design solution. The experts in design teams and construction teams who are working separately would be able to participate and exchange information concurrently as the design progresses. Design for the construction outcome would be more feasible, construction process becomes more efficient, better solutions for the design could be presented, as well as providing the most economical and suitable methods of construction, thus providing the client better value for his money.

1.3 Aims of the research

Since the question of how the buildability should be effectively implemented and analysed still remains to be investigated and manifested, based on the buildability problems faced in the construction industry, and the current opportunities in information technology to provide the solution, the research aims to:-

1. Investigate the construction planning process in order to identify the processes involved in generating the construction information and developing a construction plan.

2. Investigate the buildability practice in construction, with particular emphasis being placed on the effects and contributions which could be evaluated from the construction planning process.

3. Provide a method of buildability evaluation for designers using the construction process knowledge which is based on the construction plan.

4. Formalising and developing an integrated and intelligent knowledge based system to support designers to evaluate their design solutions in an interactive manner with the construction process. The information derived from the construction plan will be used to highlight the consequences of the design solution based on the buildability aspects.

To achieve the aims of this research, two principle knowledge areas i.e. buildability in design practice and the construction planning process are essential to support the study. How these two knowledge areas are related to design and in what way they are important to help the designer deriving a buildable solution will be discussed in detail in Chapter 2 and Chapter 3.

1.4 The objectives of the research

To meet the research aims which are based on the fact that current approaches of the project life cycle could not effectively support buildability evaluation through the incorporation of the construction planning knowledge, the objective of the study can be summarised as follows :

1. Analyse the construction planning process information requirements

    - Identify the information required from design.

- Identify the information supporting the development of the construction plan.
- Identify the factors and rules for generating the construction activities.
- Identify the factors and rules for allocating the construction resources.
- Identify the rules which govern the development of a construction plan.

2. Identify and formalise information required by designers to evaluate buildability based on the data produced from the construction planning process.

- Identify the common principles for buildability evaluation.
- Identify information required by designers to assist buildability evaluation from construction planning information.
- Identify other construction information which are required for buildability evaluation.
- Formalise information from design and construction planning to support the buildability evaluation.
- Develop a method for evaluating buildability using the design and construction planning information.

3. Perform object oriented analysis to produce a conceptual model for an integrated computer environment. Such a model should be developed in conjunction with other disciplines in order to emphasise the integration of information between the different professions. This model should represent :-

   - An information model representing the construction planning information.
   - A process model representing the construction planning process.
   - An information model representing the buildability evaluation.
   - A process model representing the buildability evaluation process.

4. Develop a prototype of an object oriented knowledge based system which will be integrated with several other construction applications such as design, estimating, site layout, etc.

5. Incorporate the prototype into the single integrated environment (SPACE).

6. Testing the prototype to validate its approach, applicability and usefulness to the industry.

1.5 Methodology of the research

To respond to the aims and objectives of this research, Figure 1.1 outlined the methodology used for the research. Among the major works involved in the research methodology include:-

- conducting literature reviews and interviews to acquire the construction planning domain and the buildability concepts applied in the construction industry to establish the problem area.
- identifying and formalising the construction planning process and design models to develop a method for buildability evaluation using the construction data.
- developing information models for both domains representing the integration approach and the proposed buildability evaluation model.
- developing and implementing an integrated object oriented knowledge based system from the proposed information models.
- evaluating the proposed information models, approach of the application, its applicability and usefulness.

- drawing conclusions of the proposed application and recommendation for future research.

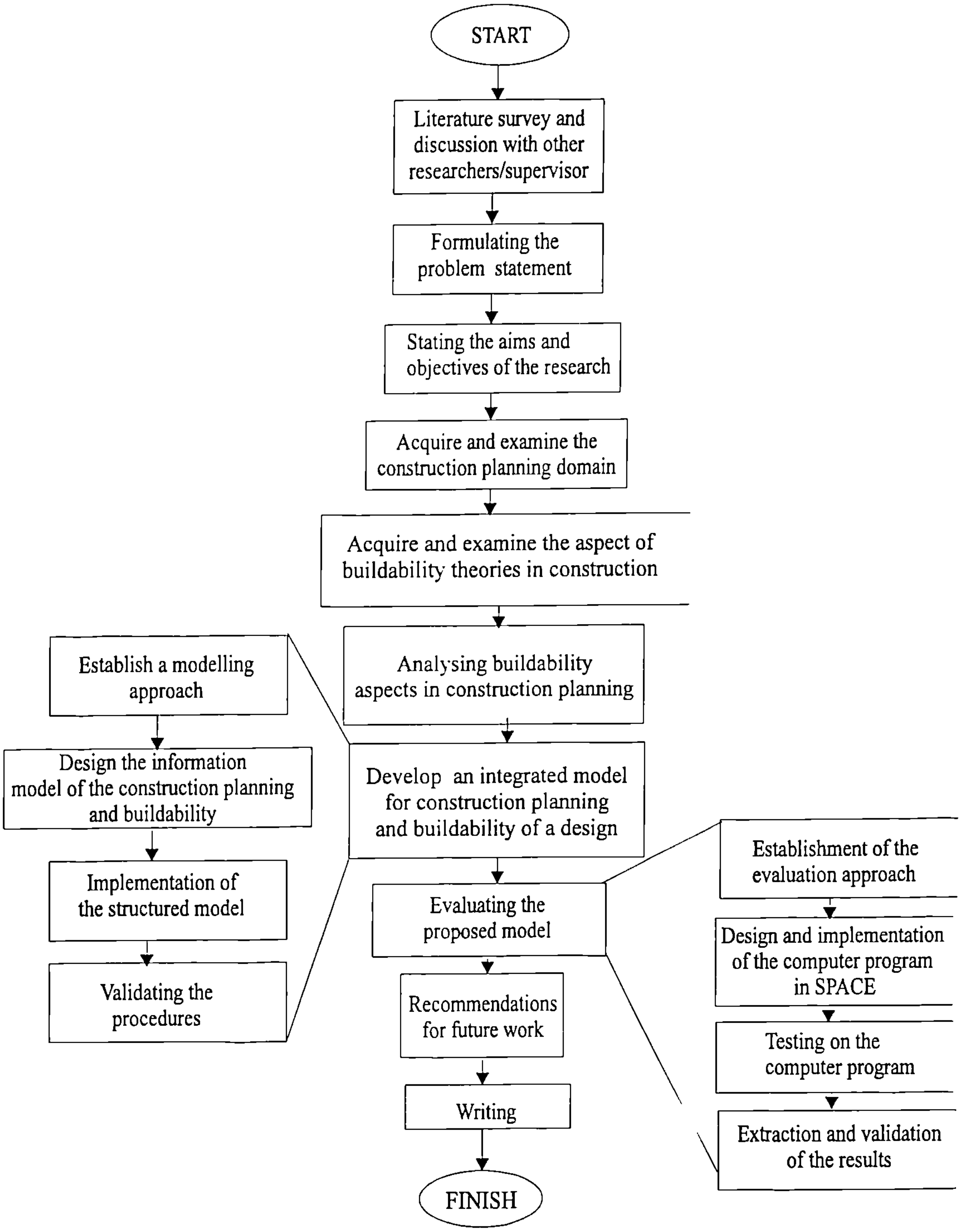


Figure 1.1 Research methodology

1.6 Scope of the research

The research main aims are to provide a framework for construction planning application which is capable of exchanging information with other construction disciplines and formalise the construction process knowledge for buildability evaluation. The prototype application system would assist the users/evaluators in an interactive manner by highlighting the consequences of the design solution based on general buildability aspects. However, while conducting and establishing the research work, various constraints have been encountered in terms of:

1. The availability of buildability information covering reinforced concrete structure.

2. The difficulty in formalising the general principles of buildability using the information from the construction planning data since buildability is not only influenced by technical matters but also by the multitude of managers.

3. The size of construction knowledge required by the construction planning process in order to develop an optimum plan to provide the information required for the feedback.

4. The technical factors in integrating and implementing the methodology for the prototype in an integrated computer application.

Based on the above constraints, the scope of the research work only covers certain subject areas, namely:-

1. The design subject to be investigated is an office building. The type of structure is only limited to reinforced concrete. Therefore, the construction plan and buildability analysis are limited to the construction process knowledge of a reinforced concrete structure.

2. The study is limited to the current documented construction activity types and their established construction methods. This limits the classification of the construction process and its required methods.

3. Since the research work will be part of an integrated system, the implementation of the conceptual models and the structured methodology developed from the research work will be limited by the software used i.e. AutoCAD/AEC™ and KAPPA-PC™ and the information provided by the system from other domains.

4. Since the allocation of the type and number of resources, productivity and construction methods to the construction activities are complex, the

prototype system used a default resource allocation methods which have been developed by other researchers.

5. Only established buildability principles which can be extracted and measured from the construction plan, in the integrated system, will be considered.

1.7 Guide to the thesis

This section will highlight the structure of the thesis and the content of each chapter.

In order to highlight the issues and the current approaches of buildability in construction, Chapter 2 describes the basic concepts of buildability, its origin and development, its scope and problems, its effects, its influences on the project life cycle, its key areas and its evaluation approaches for a project.

Since project specific construction information is generated by construction planning, Chapter 3 discusses the construction industry's approach to construction planning. The reason for this discussion is to highlight the various aspects of the construction planning processes, including the processes required to develop a construction plan and its importance to support the various aspects of the project life cycle, including its feasibility to be used as a tool to generate construction information for buildability evaluation.

Chapter 4 concentrates on the available development of application systems which supports both construction planning and buildability evaluation. It highlights the general approaches of the systems, the produced buildability results, and their system evaluation limitations.

Chapter 5 presents the integration involved in design and construction. It highlights the industry needs, the advantages of the approach and its related problems, especially the integration issues, between design and construction involved in a computer environment. The chapter also reviews the integration approaches to address the construction planning and buildability evaluation.

Chapter 6 presents the proposed quantitative approach of buildability assessment. It outlines the main information available from the construction planning process, the principles of buildability being used, and the measurement applied to evaluate the design based on the construction planning information.

Chapter 7 provides the proposed information models representing the construction planning and buildability evaluation. Information required by the domains from other disciplines is outlined for integration requirements.

Object oriented techniques were used to model the static information and dynamic processes of both domains.

Chapter 8 describes the integration framework and approach used by SPACE (Simultaneous Prototyping Applications for Construction Environment) to accommodate the various application modules in the construction environment in which CONPLAN is part of the system. The chapter also briefly highlights SPACE's components and its system architecture.

Chapter 9 presents CONPLAN (intelligent CONstruction PLANning for design rationalisation) module which is developed as a prototype to generate construction plans and buildability evaluation. The system architecture, its components, and its development as an integrated application system are outlined in this chapter.

Having developed the CONPLAN as an integrated prototype system, Chapter 10 describes the experimental approach performed on CONPLAN to evaluate the validity of its approach, applicability and its usefulness to the construction industry.

Finally the summary and conclusions derived from this study are presented in Chapter 11 together with recommendations for future work.

Chapter 2

The Research Context: The Construction Industry And Its Approach To Buildability

2.1 Introduction

Buildability has been a major criteria for successful design and construction of a project. In 1983, low buildability has been reported for causing high cost of building in UK (Allsopp, 1983). When the problem was highlighted, a number of conferences have been reorganised to investigate the concepts, applications and implications of buildability in the construction industry. Although, the construction industry has long realised the benefits of buildability to the client as well as the rest of the parties in the project. the industry is still being subjected to high level of inefficiency caused by low buildability which undoubtedly clients are paying the price for.

The problem lies in the current practice of design and construction which are performed separately. As a result of this practice. the impact of low buildability inherited in design could not be anticipated by most designers (Powell, 1983). The designers only would logically see their tasks to develop a masterpiece to satisfy the functional requirements of the project while the constructors take their tasks as construction works that required to be completed at the lowest price. Currently, since there has not been a clear understanding of how to formally incorporate the construction expertise as part of the design process (Jergeas, 1989), the problem would become more serious in the project if no effort have been made to take full account of both functions to obtain optimise solution for buildability of the project.

This chapter will describe briefly the definition, aspects, origin of the problem, scope, problem related to buildability in practice and appraisals adopted to improve buildability.

2.2 Definition of buildability

The Construction Industry Research Information Association (CIRIA) defined buildability as

"…. the extent to which the design of a building facilities ease of construction subject to overall requirements for the completed building."(CIRIA, 1983)

Construction Industry Institute (CII, 1986) defines buildability as

" the optimum integration of construction knowledge and experience in planning, engineering, procurement, and field operations to achieve overall project objectives" (Jortberg, 1984).

Illingworth (1984) defined buildability as

"... design and detailing which recognise the problems of construction process in achieving the desired result safely and at least cost to client.".

Fergusan (1989) explained buildability

"as the ability to construct a building efficiently, economically and to agreed quality levels from its constituent materials, components and sub-assemblies."

Although buildability definition given by various researchers and organisations above appear somewhat different from one another, the concept and the purpose of the definitions are mainly the same.

2.3 The origin and development of buildability in design and construction

The practice of buildability in design and construction has started since the industry history has been recorded. At the time, the practice of design and construction were conducted by single master builder who was a skill craftsman. The master builders were responsible to produce the design as well as managing and controlling the construction works. Because of this fact, the problem related to construction processes was taken naturally into the design consideration when the design was formulated (Jergeas, 1989).

However, as projects become increasingly complex due to the emergence of new building materials, construction technology, users demand for high technology of service facilities, etc. various professions have emerged to provide the various demands in design and construction. Later, it has been suggested (Bowley, 1966) that the dichotomy in design and construction may be the cause of the difference between rapid rate of progress in science and technology and the slow pace with which advances are applied in the building process.

The establishment of various professions such as architecture, structural engineers, services engineers, landscape architects, builders, specialist contractors, etc. which reinforced the division in the industry were slowly encountered since the 18th century (Walker, 1989). The split of design and construction paved the way to the establishment of architecture as a profession. Through the passing of a supplementary charter of the Royal Institute of British Architects in 1887, the separation of the design profession from actual construction of buildings, was concluded, in which design activity was granted as a profession of architects.

Further division in the industry accelerated since then, when greater understanding of engineering principles and others specialised areas were required to fulfil the growing needs of the construction industry. This unavoidable needs to provide the distinct roles and responsibilities which could not be fulfilled by architects alone, eventually disseminated the design task into several other specialist tasks, such as structural engineers, services engineers, civil engineers, quantity surveyors, etc.

Nevertheless, the separation of design and construction in the industry is considered as the practical approach to suite UK requirements and was not challenged until 1962, when a report (Emmerson Report, 1962) was produced, suggesting that the separation was considered as major contributory factor to the inefficiency of the U.K construction industry. This investigation inspired further awareness of buildability, which in 1964, further confirmation was noted (The Banwell Report, 1964) where it was suggested that

> " design and construction must be considered together and that in the traditional contracting situation, the contractor is too far removed from the design stage at which his specialist knowledge and techniques could be put to invaluable use.... the builder is a member of the team and should be in it from the start."

Later in 1975, The Wood Report (NEDO, 1975) was produced recognising the needs to improve the design and construction interrelationship i.e. buildability of a project. It was noted that

> "the traditional separation between design and construction was found to have diminished with consequent advantages all around.......

contractors have much to offer at the design stage, especially by way of advice on constructional implications of design solutions and decisions ... yet, methods of procurement are still such that they are brought in too late for their advice and experience to be of practical use..... the original problems still exist."

Again in 1980's , various strong new opinions from within the construction industry emerged suggesting that this traditional separation of design and construction phases of the building process was primarily responsible for the lack of buildability of present construction projects (Griffith, 1984). Despite CIRIA (1983) acknowledgement that ease of construction may be influenced by many organisational, technical. managerial and environmental considerations, the main contribution was thought to lie in those factors which fall within the influence or control of the design team.

2.4 Scope of buildability

The definition of buildability described by CIRIA (1983), suggests that the buildability of a project is a direct consequence of design intentions, hence the key to good buildability of a project is believed to lie at the beginning of the design phase. However, the definition suggested by the Constructability Task Force of the Construction Industry Institute (CII. 1986), outlines the scope of buildability that lies throughout the spectrum of the building process, i.e. the buildability is brought about by continuous process of integrating the knowledge and experience of the designers/consultants, the builders, subcontractors and suppliers from inception to completion of a project.

Since CIRIA (1983) also acknowledged that the ease of construction may be influenced by many organisational, technical, managerial and environmental considerations, therefore, each participant in the project life cycle, is responsible to initiate buildability improvements. As every participant at every stage would have different views on the implementation of buildability to a project, the influences of the buildability improvements would come from all stages of the project life cycle i.e. from briefing and feasibility stages, design, procurement, construction, maintenance and demolition (Ferguson, 1989).

Griffith (1984 &1985) suggested in his buildability investigation on a Health Centre Project, that besides design matters, the managerial aspects are the greatest influence to increase productivity and achieving buildability. To highlight the significant influences of the management on buildability, he summarised that

> " Managerial capability can overcome inadequate design but a well rationalised design will not overcome inadequate management."

Although it is essential for buildability to be implemented at every stage of the project life cycle through the perspectives and knowledge of the participants (as they have different implications to the project), a special approach for evaluating the buildability at each of these stage is required (Kalay, 1991). Although the buildability aspects could be influenced by various managerial and project oriented aspects such as environmental, political, economical etc., currently, majority of work done on buildability only focused on the effect of design on construction and vice versa.

2.5 The effect of buildability on the project

Buildability affects various participants of the project as well as the progress of the project in numerous ways (O' Connor, 1985). In its simplest message CIRIA (1983) has suggested that

> "Good buildability leads to major cost benefits for clients, designers and builders."

It affects the construction project in many aspects such as project cost, project duration, quality, productivity, safety, method of assembly, site layout, maintainability, etc. (Ferguson,1989). These causes of buildability may affect the various parties in the project either positively or negatively. Reducing the negative factors of the buildability aspects such as expanding the repetition of similar specifications used in the building elements will influence the positive result, such as higher productivity, improve the utilisation of resources, etc. If the negative factors of the buildability aspects are left unchallenged i.e. building elements vary in shape and specification, it would reduce, or influence the buildability level of the project.

The utmost consequence from bad buildability of a project is the cost to the client either through lost of investment or increase of project cost (Allsopp, 1983). In many occasions, the project also could be delayed by variation orders which would normally be issued to rectify design problems. For the designers, they could possibly lose the opportunity to take a new project as they are occupied with extra redesign works caused by impractical designs found during construction in the current project.

Furthermore, depending on the nature of the variation and redesign requirements for the running project, it could also effect the designers reputation and client confidence. Contractors would also lose the opportunity to obtain new projects as their resources are held up in current projects. In short bad buildability leads to increased cost, delays the project, and reduces benefits to every parties in the project (Coombs, 1983). On the other hand, the consequences of good buildability projects are also varied, for example, the clients could have their building project completed within time and budget, without additional major costs to variation, minimum disruption, efficient operation on site, and aesthetically and functionally pleasant. The designers could have less design problems on site during construction as well as when commissioning since their designs will have been evaluated base on the operational requirements on site. The designers reputation also increase with a good deliverable designed project (Adam, 1989; Griffith, 1984).

If buildability aspects are considered by the team at the early stage in design, the type of construction methods and its construction activities can be accurately be allocated in advance. Thus, the project can be efficiently constructed as accurate construction project planning and its predefined construction methods can be developed. The expected project duration also might be reduced, since less variation orders would be issued and interruptions caused by impractical design details are almost eliminated. The construction of the project would be able to run smoothly since less conflict between parties over design solution would be encountered, etc. Figures 2.1 below shows the stages for a project life cycle and indicate how progress made on each stage could lead to decreasing influence from designer and increasing in the project expenditure.

2.6 Buildability in project life cycle

Buildability in practice has certain time frames when it is most applicable in the project and when it no longer has any significant effect. The development of a project evolves through different stages and involves many participants over its life cycle. The effects and contributions of buildability improvements by each of the participants vary accordingly. Although CIRIA (1983) has suggested that, to achieve good buildability, both designers and builders must be able to see the whole construction process through each others eyes, as the project develops through each stage of its life cycle; the opportunity and the effects of buildability improvements becoming less significant.

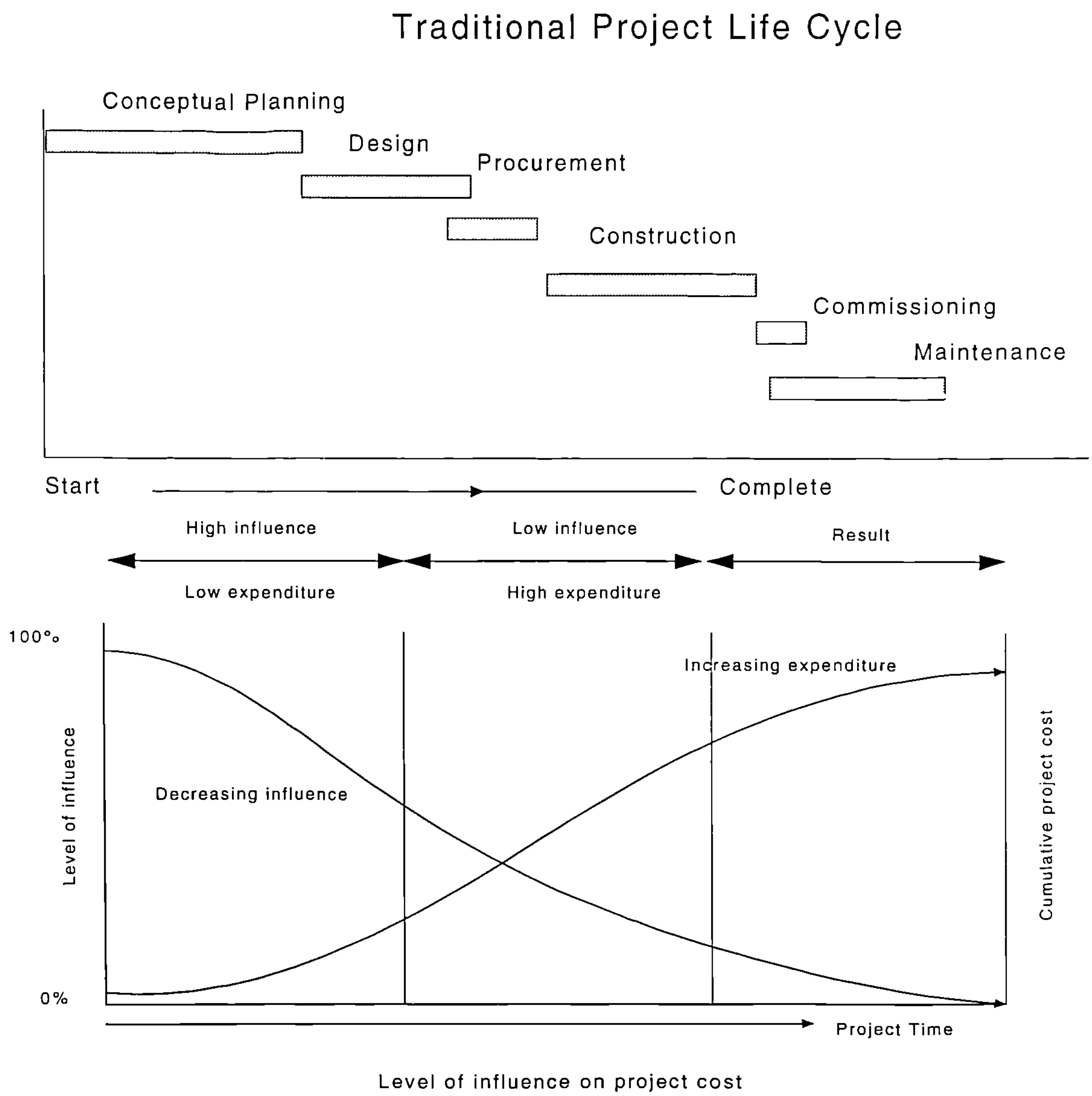


Figure 2.1 Project life cycle and designers level of influence

Among many of the participants involved in the project, the designers are expected to play the central role for buildability improvement, since they are responsible for most of the technical problems which arise in the project during design, in the erection of the project and commissioning of the project (Stone, 1983; Alkass, *et al.*, 1991). For example, at the design stage, besides the designers are obligated to produce a design which conforms to the clients requirements they should also consider their detailed design implications to the construction process (Jergeas, 1989; Fisher, 1991).

Figure 2.1. illustrates the stages of project life cycle and the designers level of influence on the project cost over the project time. As the project progresses, the designers level of influence decreases while the project expenditure increases. The graph also illustrates that the best time to secure good buildability of a design is at the earlier stages of the projects development.

Hon, *et al.* (1989) stated that although for certain stages of the project life cycle, different buildability measures should be employed by the participants of the project, the greatest opportunity for improving buildability however, occurs during the early project phases. O' Connor *et al.* (1986) described that to achieve a good buildable project, the three major stages of project life cycle i.e. design, procurement and construction are essential for implementing the buildability improvements. Since each of the stages would have different impacts on buildability, it requires different types of approach for buildability improvements. Figure 2.2 depicts O'Connor *et al.* (1986 & 1987) illustration of the project stages and the project participants requirements for improving buildability of a project.

Besides producing buildable detailed design, the communication of their design solution to the other parties involved in the project is also considered as one of the important factors for buildability, especially for the contractors and suppliers (O' Connor *et al.*, 1986). Efficient and effective format of communication would have to be setup with which complete detailed drawings, specifications and instructions are clearly provided. The effective and efficient communication would be essential to avoid misinterpretation and misunderstanding of the design solutions by other parties.

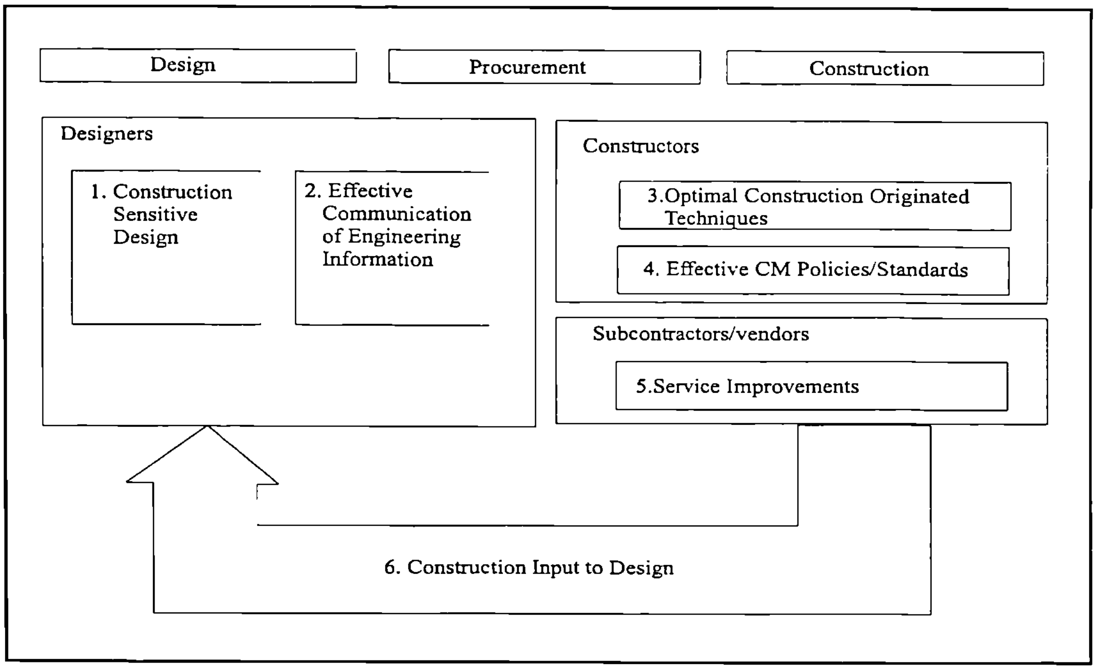


Figure 2.2 The project buildability improvement life cycle (O' Connor *et al.*, 1986).

While at the construction stage, as part of buildability aspects required for project improvements, the contractors are entrusted to use optimal construction-originated construction techniques and effective construction resource management policies/standards (O' Connor *et al.,* 1986). The contractors also have to contemplate how to use the most economical and efficient methods of construction for the project. It also suggested by O' Connor *et al.*(1986 & 1987) that the vendor or subcontractor could also effect buildability at the construction stage by the standard of services they provided to the main contractor.

2.7 The key areas of buildability

The aim of buildability is to improve the efficiency of the overall building process by developing construction sensitive designs (Hon, *et al.*. 1989). The expected results from implementing buildability are efficient and effective construction of a building, with an economical project cost and at agreed quality specified by the clients. Although most researchers and organisations involve in buildability agree on the purpose of buildability, which is to ease the construction activities without effecting the quality and performance required, they differ in the aspects of buildability and at which stages of the project life cycle it is essential that buildability is implemented in the project.

From the range of buildability definitions given earlier, it is generally agreed that the aspects of buildability are contributed at all stages of the project life cycle, i.e. from briefing stage to maintenance and demolition. However, amongst all the stages of the project, the most prominent stages where buildability aspects have been properly defined and structured for implementation is design and construction (Fergusan, 1989; Illingworth, 1984; CIRIA, 1983; O' Connor , 1985; O' Connor *et al.*,1986).

Since, the implementation of buildability requires all parties involved in the design and construction to work together to secure good buildability, various guidelines have been produced to be observed and implemented for buildability of the project. CII Constructability Task Force (O'Connor *et al.*, 1986) described seven guidelines for accomplishing buildability in project development;

1. Construction-driven planning and programming.

   The objective can be fulfilled by developing a general construction programme before design and procurement schedules are developed. The programme is characterised by creating a schedule from the required date the project has to be completed and working backward to establish the duration of various tasks, i.e. start-up, checkout phase, the date where the structure has to be ready for services equipment, etc. The construction programme developed would be able to indicate when the issuance of drawings, specifications and delivery of materials should be placed. After the drawings and specifications have been completed, further detailed and finalised schedules would be developed for the construction works in an interactive manner.

2. Design simplification.

   Complex detailing which require difficult construction methods, could take longer construction time and costly resources and therefore should be avoided. Design should enable efficient construction. Although safety, operability, maintainability and aesthetics are the usual project objectives which frequently transcend buildability, the design layout and design details may often be modified to enhance buildability without sacrificing the project objectives.

3. Standardisation and repetition of design elements. This would reduce the learning curve and increase construction activity efficiency. Savings could be realised when the number of variations of components is kept to a minimum as it could simplify material procurement and materials management from fewer differing materials.

4. Specification development for construction efficiency. Designers are recommended to use specifications which can provide smooth and efficient construction methods. The appropriate use of basis design specifications and avoidance of misapplied materials specifications could simplify the construction process.

5. Modular/preassembly designs should be developed to facilitate prefabrication, transportation and installation. The benefit of modular/preassembly designs include improved task productivity, parallel sequencing of activity, increased safety, improved quality control and a reduced need for scaffolding.

6. Design should allow for accessibility of labour, materials and plant. Accessibility of the resources to site is a major requirements for effective and efficient construction. Projects would be delayed or incur high construction cost if accessibility was not taken into consideration when designing the project.

7. Design should facilitate construction under adverse weather conditions.

Similar to the above objective but expressed in different words, CIRIA (1983) identify seven guidelines for both designer and contractor to follow in order to obtain good buildability. The guidelines proposed that:

1. A through investigation of the site conditions should be made and worked into the completed design before any documentation is started.

2. The layout and phased completion of sections of the building should recognise the requirements of site access, materials handling and the construction sequence.

3. The method of construction should encourage the most effective sequence and should recognise the benefits of completing a "dry envelope" early on in the contract.

4. Designers should plan simplicity of assembly during the fitting out of the building and for a logical and ordered sequence of trades.

5. Maximum repetition and standardisation of components and building elements should be adopted.

6. Building designs should be prepared with achievable and appropriate tolerances.

7. Robust and suitable materials to allow for site conditions and the capability of being protected should be specified.

Although both guidelines, provide the general recommendations for implementing good buildability in a project, detailed breakdown of the guidelines for analysis and evaluation studies are still required in order to determine the scale of buildability quantitatively when a building becomes difficult and uneconomic to build. For example, how many repetitions of specification for certain types of element is good enough for buildability to the project.

2.8 Applying buildability to projects

In general, the buildability of any construction project depends on five main participants, the client, the designers, the contractors, the manufacturers of building materials, and the institutional environment (local authority, banks. etc.). Each participant will have a time frame for taking part in the project development where their decisions could significantly affect the buildability improvement of the project. The clients contribute to buildability of the project by their skill in pointing out their needs at the briefing stage. prior to the preparation of the design and then assessing the value of the solutions put forward by the designers (Stone, 1983; O' Connor, 1985).

Within the brief and the design stage, designers apply their buildability improvement by providing an operable and economical design solution that meets clients needs as well as facilitate overall requirements to ease the construction for the project. The constructors on the other hand. who are normally considered as a third party in the project, contribute in applying the buildability improvements to the project by providing an appropriate number of labour and the size of organisation with an efficient and speedy working of construction methods to realise the project. The manufacturers of building materials contribute to buildability of the project by providing quality building materials that fulfil the intended used on the site. The institutional environment play their roles in buildability of the project by providing efficient services required by the construction industry.

Although some suggestions for applying buildability improvements from CIRIA (1983) and O'Connor *et al.* (1986) have specified the area of responsibility of the participants involved in a project as described above, they do not address the specific procedures with which the participants could implement the buildability procedure in order to improve the buildability aspects of the project, except general guidelines to reduce the problem.

The absence of the specific procedure for improving the buildability is caused by poor interaction between all the project participants due to the procurement system employed. sequential process of project development, project participants are represented from different organisation, etc. In general the guidelines suggested for the designers to implement the buildability aspects in design, they have to analyse their design from the constructional point of view and to make appropriate adjustments to accommodate such views in their design solution.

Based on this general suggestion, the application of buildability in design requires two stages. First, the designers have to conduct an analytical approach to their design to check against buildability aspects and second, the designers have to take specific action to present the outcome of the analysis in an acceptable format for project communication and implementation.

2.9 Evaluating buildability

There are numerous aspects of design and construction which could be subjected to buildability evaluation such as dimension and tolerances, practical detailing, quality of information, selection of procurement system, site constraints, allocation of project construction cost and time, selection of construction methods, arrangement of site facilities, construction planning, etc. (Gray, 1983 & 1986; Illingworth, 1984: Ferguson, 1989; Jergeas, 1989; Underwood, 1995, Fisher, 1993). Figure 2.4 illustrate several stages of buildability evaluation which could be performed in the project development life cycle. Depending on the availability of information, some of these buildability aspects could only be performed at certain project development stages .

In a normal practice, the buildability evaluation is applied to a project by making comparisons of the new design with previous project experiences on buildability. Since the evaluation required previous project experiences, this capability is only limited to the experienced designers or constructors (Jergeas, 1989). Although numerous buildability studies have been investigated in the projects, however, only few researchers have addressed the theoretical procedure to analyse and implement these aspects on a design (Jergeas, 1989, Fisher & Aalami, 1994).

Since the performed studies on buildability are varied and numerous, the result of the studies also varied accordingly i.e. from producing general guidelines of buildability to specific application systems addressing specific areas of buildability.

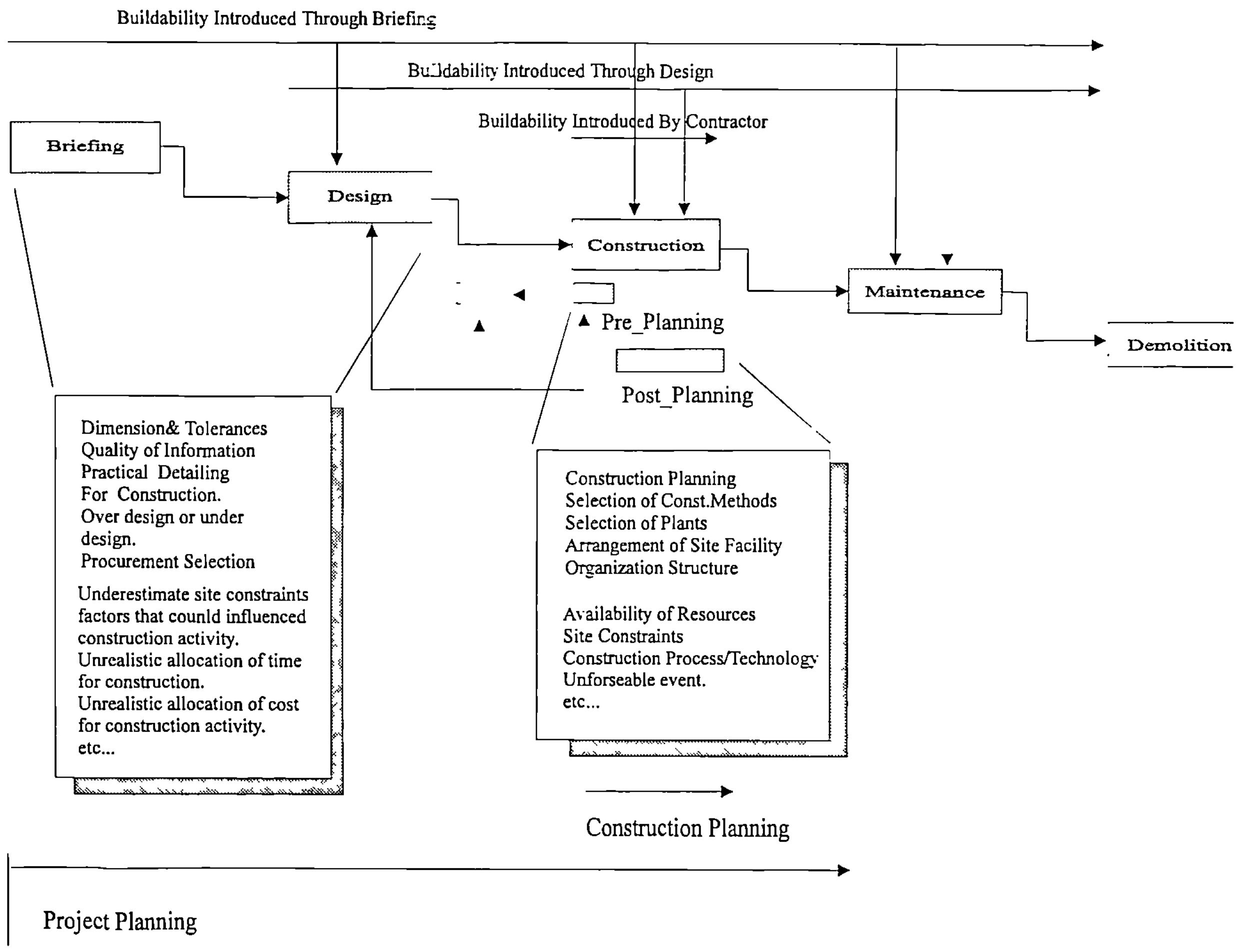


Figure 2.4 The project life cycle and buildability evaluation.

CIRIA(1983), CII(1986), Hon *et al*, (1989) and Ferguson (1989) for examples have produced general documentation giving various designs which show bad examples of buildability and the resolution adopted to amend the faults. Besides the guidelines, advance works have also been carried out to identify the low level aspects of buildability such as assembly and conversion of building materials (Ferguson, 1989), design against tolerances (Underwood, 1995), buildability against selection of standard formwork (Fisher, 1991 & 1993), buildability against time and cost (Gray, 1986; Stretton & Steven,1989), buildability against design detailing (Jergeas, 1989) and buildability design against construction methods (Fisher & Aalami, 1994).

2.10 The approach of buildability assessments

Majority of the research works on buildability have provided the industry with the general guidelines on what needs to be done to improve buildability, and when the implementation of the buildability is important in a project life cycle. Nevertheless, in spite of its importance, few researchers have recommended the practical solutions on how to evaluate the aspects of the buildability.

Gray (1983) highlighted that there was "no simple answer to the problem of evaluating the construction implications of a design" since, in his opinion, the construction process is extremely complex in nature and the result being that there was no best way to analyses the process. However, Gray (1983) suggested that the evaluation should consider the consequences from several different views, such as the time to construct, cost of construction and sequence of operations. Moore (1996) also suggested that the development of the buildability evaluation method is slow for two main reasons, first the difficulty to define buildability (within each stage of the project life cycle) in the context of its implication on construction and secondly how to evaluate a project which has little consideration to buildability.

However, the first generic qualitative measuring approach which could identify the effects of buildability aspects of a design was introduced by Ferguson (1989). The measurement was done by defining the 'hierarchy of difficulty' of assembly of the element or component of the building. The hierarchy is divided into five steps, i.e. assembly possible, assembly only possible with extreme difficulty, assembly possible without difficulty, assembly straightforward but perverse and assembly easy. The idea behind these hierarchy principles is for designers to measure the topological relationship of the design components or elements or sub-assemblies based on their interpretation as how difficult these elements are assembled or dissembled.

Although, the measurement on 'hierarchy of difficulty' provided a basic approach for identifying any component, materials or sub-assemblies for ease of assembly from various design examples, to implement the idea, it requires the designers to be imaginative with these principles when adopting and applying it to their design. However, since the method of measurement of this 'hierarchy of difficulty' is based on general rules on what the designers should observe to identify the buildability problem, further work to formulate this theory into a quantitative or an analytical technique in which design data can be collected and analysed is still to be developed.

The same basic buildability principles was also used by Fisher (1993), however, the research work has managed to provide specific feedback in which the designers could directly evaluate their proposed layout and dimensioning of reinforced concrete structures (building) with the available proprietary formwork system. The evaluation (Fisher, 1993) will argue about the geometrical and topological properties of the design before providing buildability answers to designers whether a selected construction method (in this case formwork system) can be used efficiently for the project. The facts about the applicability of the formwork selected for the structure is compared with the geometrical data (thickness, height, shape etc.) of all the structures elements i.e. beam, column, wall and slab. If the selected formwork is proved not suitable either caused by dimension or layout, the designers can change the proprietary formwork to a different system or change the entire arrangement of the structures layout and dimensions.

Such principles and approach was also used by Jergeas (1989), however the aspect of buildability was focused on the effect of design detail on construction. Based on his research hypothesis, that design detail has significant influence on buildability, Jergeas (1989) has developed an evaluation approach, that could provide designers with an assessment system of detail design through a series of questions. By utilising previous project detail designs of a retaining wall system, and based on information provided by the designers, the evaluation approach would search a suitable wall system that meets design criteria defined by the user as well as recommending its components and the wall type construction that would have less of a buildability problem. Before recommending the wall system, the evaluation approach would reason about the weight of the retaining wall, lateral loads resistance, deterioration factor, services installation within the wall. weather conditions, degree of inspection required and type and complexity of formwork to be used. A report which shows the cost activity breakdown of the wall system is also displayed for comparison.

Another aspect of buildability which has considerable impact on a project is tolerances and dimensions of different building assemblies when applied to concrete frame structures. The studies on tolerances and dimensions for structure frames in which cladding and lining are to be incorporated in the design has been investigated by Underwood (1995). The aim of the studies was to provide the designers with a buildability evaluation that would assist the designers on the grid and layout dimensions of the concrete frame when a cladding and lining type is chosen for the structure. The evaluation would use the selected cladding/lining type, dimensions and its tolerance and the structure elements dimensions and tolerances i.e. beam, floor to floor height to justify the buildability of the selected cladding system and the structure grid and layout dimension system. Accordingly based on the allowable tolerances of the cladding or lining that have been selected, all the grid and layout dimensions either horizontally or vertically would be adjusted. A prototype system which provides the analysis and the solution was build as part of the research work.

Besides the above approaches which are used to analyse buildability of a project, the general quantitative accepted measurement for comparing design solutions developed by other researchers is through using costs and duration derive from the design. This measurement is done by calculating the cost and duration required to build a specific type of project, based on the general construction activity such as groundwork, superstructure, roof, services, etc. The result from the construction activity in the system will indicate whether the design is costly, economic or efficient to be build.

Comparatively, based on the general activity breakdown of the project, i.e. superstructure or substructure or roof or services, if the design show high construction costs and longer duration, the designers can decide either to redesign or maintain the same design solution. This type of analysis for buildability was produced by Stretton and Steven (1989) and Gray (1986).

Although the systems provided by Fisher (1993), Jergeas (1989) and Underwood (1995) solve specific problems of buildability by matching the design with the available proprietary formwork system, previous detail designs or cladding type on the market, the systems do not provide construction evidence which are based on cost, time and resources or the construction processes that could be concluded if the recommendations were overruled or taken on board. With reference to the result of the analysis, the designers are only given an opportunity to alter their selected proprietary system or change the structure, size and dimensional layout.

On the other hand, the evaluation provided in Gray (1986) and Stretton and Steven (1989) gave general indication of buildability impacts on cost, resources and time, they do not highlight specifically the elements or factors for which the buildability factors have been considered such as whether it was caused by irregular elementary dimensions, incompatible design layout with available formwork systems, difficulty of assembly due to non-standardised elements, dimensional intolerance, specifications or by the factor of difficulty in the construction processes.

Even though some of the evaluation systems provide the specific feedback on design such as Fisher (1993), Underwood (1995), Jergeas (1989) etc., they only represent a subset of buildability optimisation. Designers still face problems to compare and identify other related areas of buildability. Furthermore, the generic feedback provided by Gray (1986) and, Stretton and Steven (1989) which present the time and cost of projects can only be used as early risk indications of buildability. As to which part of the design element requires close evaluation for buildability, is impossible to be indicated from the system.

Having outlined the theoretical aspects of buildability alone could not fully assist the designers to produce a good buildable construction project. Therefore, some researchers also have formalised the basic theoretical aspects of identifying and solving the buildability factors into a computer system to provide an automatic buildability assessment system. Chapter 4 will address these applications and explain a new proposal to measure buildability of various elements of the design. The proposed evaluation would consider the consequences of buildability from the general principles of buildability improvements which would be able to provide the result of the analysis by indicating the time to construct, cost of construction, sequence of operations, trade and plant usability, etc.

2.11 Summary

In this chapter the definition, the key concepts and the approach of buildability have been discussed. The aim of the review is to highlight the problems of buildability in the construction industry. In the succeeding chapter, a construction planning function is reviewed to indicate its processes, approaches, and usability of the information it generates for the construction industry.

Chapter 3
The Construction Industry And Its Approach To Construction Planning Process

3.1 Introduction

Over many years, the construction planning process has been recognised as a critical function in the project life cycle. The construction planning process has become not only essential for contractors to provide the outlines of construction activities required for the project, but also as a tool for the designer to predict the effect of their design on construction in terms of cost, time and buildability. In recent years, with growing sophistication of several application systems used in the construction planning process, such as the project management system, the knowledge based system, and the database management system, the construction planning process has become an important contributor to the construction process. Besides the applications have being used mainly to speed up the generation of a construction plan for executing, monitoring and controlling the construction activities, it also has been used for assessing the buildability of a design and improving project performance (Mohan, 1990; Morad & Beliveau, 1991; Fisher *et al.*,1995 ; Moore, 1996).

Although the available information technology could provide enormous advantages for the construction planning process, and increase the added value of the process, the development of an automated construction planning process still face many obstacles (Hendrickson & Maher, 1989; Aouad, 1991; Kahkonen, 1993; Yamazaki, 1993). Among the major problems that slowed down the automation of construction planning process are structuring the construction planning process knowledge, capturing the scope of design and construction information required for a particular project, providing an optimum solution and presenting various scopes and levels of the construction plan (Benjamin *et al.,* 1990; Navinchandra *et al.*, 1988; Kartam & Levitt, 1990).

This chapter will describe the various fundamental aspects of the construction planning process and its contributions to the construction of a project and to the parties involved. The aim is to highlight the complexity of various processes involved before formalising it to support buildability evaluation.

3.2 Definition

Construction planning is a task performed mainly by a construction planner to establish a construction plan, or construction schedule, in which the construction activities, their dependency, resources and duration required for a project are outlined. The outcome of the construction planning process is the construction plan. The construction plan is essential for construction, since it would become the basic reference for executing, monitoring and controlling the construction work on site.

Currie and Drabble (1992) describes, the word 'plan' which simply means as creating a set of actions to meet some predefined objectives while a 'planning system' (whether it is used in construction, manufacturing or other industrial sectors) is the process responsible for producing a plan defining a possible solution to a specified problem. Ackoff (1970) defined planning as a decision making process performed in advance of action, which endeavours to design a desired future and effective ways of bringing it about. Laufer (1990) describes planning as a decision making process that employs formal procedures and techniques, documented presentation (in the form of plans) and implementation, which evolves through a hierarchical process from general outlines into objectives, to elaboration of means and constraints that lead to a detailed course of action.

3. 3 The aspects of the construction planning process

Research on the construction planning reviewed that construction planning processes focus on the development of a framework within which site activities will be carried out, reviewing project progress at regular intervals and taking appropriate measures to keep the project in line with the planned progress (Erskine-Murray, 1972; Cooke, 1992; Laufer and Tucker, 1987; Ahuja *et al.*, 1994). The main purpose of the construction planning is primarily to reduce the uncertainty that exists before or while a project is executed, avoiding project crisis and improve efficiency of the operation by clarifying the objectives (Ahuja *et al.,* 1994).

As a normal practice in the construction industry, the construction planning process is carried out by the contractor to produce the construction plan before the actual construction work takes place on site. Based on estimated qualitative analysis and judgement, the construction plan represents of what, how, when and why factors of the contractor's intention to realise the project. Therefore, the production of the project construction plan demands variety and extensive knowledge about planning and scheduling principles, the project objectives, the availability of construction techniques and methods, types and use of various construction resources, construction safety, construction regulations, and the interpretation of designs and specifications of a project. Each of these significantly affect the accuracy of the construction plan.

Although the construction planning principles are generally standard in the construction industry, the approach to the whole planning process appears to vary widely between companies (Cooke, 1992). The construction planning processes itself is bound by various factors such as the construction planners knowledge and experience, the type and description of the project, the quality of construction information available, the procurement type of the project, the details of the planning required, the time allocated for planning and the construction company policy on the construction planning process.

Besides technical matters related to a design, the production of the construction plan is also affected by managerial factors such as project organisation or the management decisions, economical factors such as least cost, or fast completion, or availability of resources, technical factors such as suitability, operability and efficiency of the construction methods selected, and the surrounding environments such as weather or local conditions. Since the outline of the construction plan is easily affected by these factors, most of the initial produced plan would be replanned when the variable factors that determined the early decision criteria changed.

3.4 The stages of the construction planning process

Construction planning is a goal-oriented task and evolves through several stages. The construction planning process evolves through three specific stages within the construction period. Laufer (1990) considered the evolution of the planning process as a problem solving task. The first stage of the construction planning process involves problem definition, second is providing solution and lastly monitoring and controlling the execution of the solution. At each of these stages different approaches and certain types of information are required.

During problem definition, the construction planner normally refers to project documents provided by the design team such as bill of quantity, specification, architecture/structural/services drawings, specifications, site report and contract documents to understand the nature of the project and its construction requirements. As much information as possible is collated from the project documents to identify the required construction activities. Since, the identification of the construction activities vary depending on the level of use, and the detail of representation required on the construction plan, at this stage, it is essential for the construction planner to decide on the correct identification and scope of the construction activities.

With the identified construction activities, the construction planner in co-operation with other construction management teams in the project such as estimator, site engineer, plant manager etc. would provide the solution by describing how each construction activity would be carried out, allocate appropriate construction resources, identify the dependency between all the construction activities and calculate their duration. During this stage, information is extensively exchanged between the construction management team to derive with the solution such as on selection of construction methods, use of resources, productivity, cost, etc. Various analyses and evaluation would be performed by the construction management team to produce the information required to obtain the construction solutions for the plan. Once the solution is available, depending on the analysis and presentation required for the project, such information are then used to create the PERT (Program

Evaluation and Review Techniques) evaluation, CPM (Critical Path Method) network, line of balance, resources profile, cast flow, and bar chart (Davis, 1974).

The third stage of the construction planning process is monitoring and controlling the implemented solution as presented in the bar chart, PERT or CPM. During this stage, various information on the current state of construction such as why the planned solution did not work or was delayed, how many days has the project fallen behind the plan and what activity can be altered to cope with the demands would be examined. New information emerged from the state of the construction activities would be used with other construction management team decisions to update the construction plan.

Any deviation of the plan either caused by interference such as delay, variation order, rework, labour unavailability, disputes and weather would require the construction planner to revise the planned solution and replan the construction plan again. If the solution outlined in the construction plan did not perform as desired during the construction stage, then corrective measures are taken either by increasing the number of resources, assigning overtime or changing the activity plan. If the project is delayed, the construction planner would have to evaluate whether adding more resources or adjusting, e.g. crashing or relaxing, the other construction activities to bring the state of the construction progress as planned earlier. If a variation order was introduced where new work is required, the construction planning process would be replanned while maintaining other unaffected construction activities solutions in the earlier construction plan. When major amendments are required on the original solution, the construction planning process would probably have to be repeated.

3.5 Developing the construction plan

Developing a construction plan involves selection of construction technology, identifying the construction activities, and their required resources and duration, and recognising any interactions or constraints among different activities. In order to develop the construction plan. various processes are involved such as gathering project information, defining construction activities, selecting construction methods, sequencing the activities, resource allocating and optimising the construction plan.

Each of these processes would significantly influence the accuracy and effectiveness of the plan. Laufer and Tucker (1987) suggested that the development of a construction plan faces several risks that could lead to it being ineffective and inefficient such as conceptual. administrative and environmental. Imperfect formulation of the problem, making wrong assumptions or choosing incorrect decision criteria is considered part of the conceptual risk. Administrative risk refers to the resulting failure of the management to implement the solutions while environmental risk refers to unanticipated environment changes which may spoil even a well conceived and implemented plan. Although numerous factors cannot be completely foresighted and controlled such as variability in the performance of a task and interference from external events in the development of a plan, with careful evaluation and defined logic, a good plan can be produced within the available time (Bennett & Ormerod,1984) .

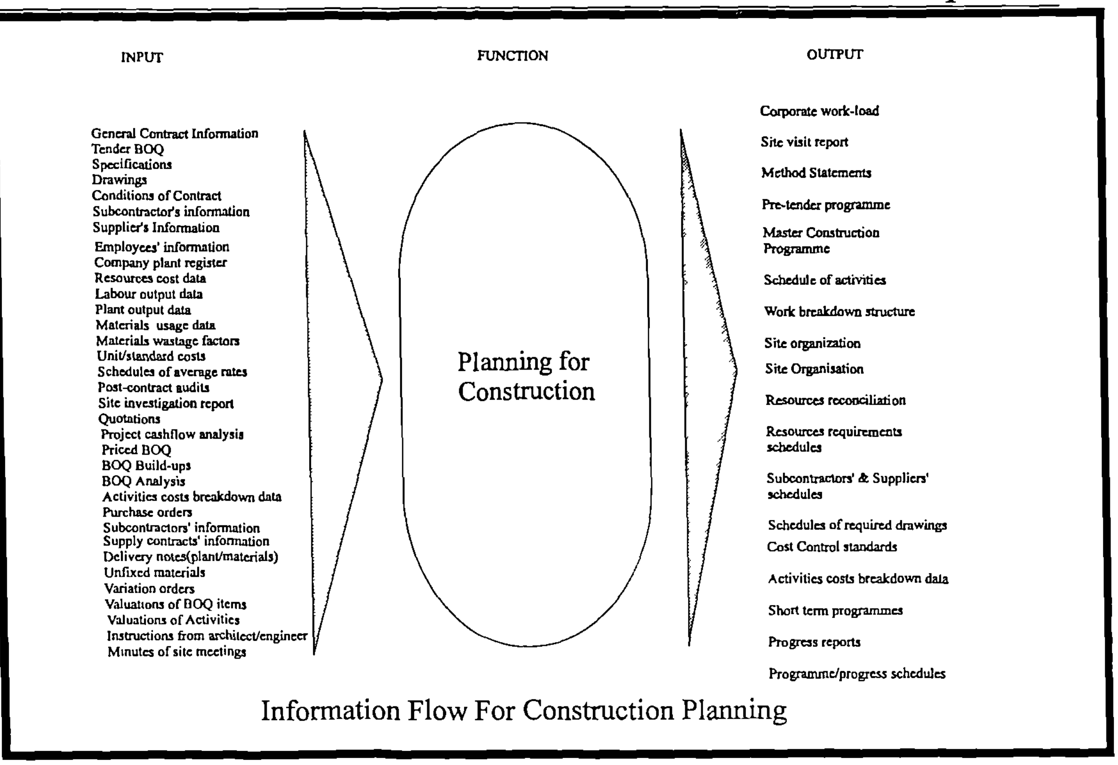
To avoid inaccurate construction plans, firstly, the construction planner has to define clearly the objectives of the project such as the expected finish date of the project, the expected cost of the construction, etc. and secondly, to gather as much information about the project and surrounding environment as possible and to find the best practical solutions for the plan. Described below are the constituted processes for the construction planning process to arrive with the construction plan.

3.5.1 Gathering project information

Gathering relevant project information is the first step to providing the construction plan. The importance of this step has been stressed by Steiner (1979) and Galbraith (1972). Dermer (1977) also noted that the essence of planning is collecting information and making decisions. Gathering information for construction planning requires great effort, skill and competency in data collection techniques (Laufer & Tucker, 1988). Laufer and Tucker (1988) also stressed that the information gathering tasks normally consume longer time, since it involves systematic gathering of internal and external data such as resources availability, cost and productivity of resources, etc.

Construction planners are also always subjected to difficulty when gathering the internal or external information (Laufer and Tucker, 1988). For this reason much of the information used for developing the construction plan, occasionally are incomplete and to some extent are inaccurate. For example, when drawings and specifications of a detail design are not completed before the construction stage, the construction planner has to make assumptions based on what is available.

Nevertheless, the main source of information normally referred to by construction planners to develop the project specific construction plan are contract documents, bill of quantity, detailed drawings, specifications, site investigation report, construction methods, productivity records of labour and plant, availability and cost of resources, internal management policy, supplier's information, etc. as shown in Figure 3.1. Besides the information provided from the project documents, at some point, depending on the degree of planning and control, as well as the scope and contents of detailed information required from the construction plan, some advance information gathering may be needed to assist the planners such as when evaluating new construction methods, site layout analysis, new study on work flow etc.



Information Flow For Construction Planning

Figure 3.1 The general source and the generated information of construction planning process (Ndekugri I.E & McCaffer R., 1988).

In normal practice, the information abstracted from the above sources are used by the construction planner to identify the type of construction activities (what should be done?), the construction methods (how should the activities be performed?), their appropriate type of resources (who should perform each activity and with what means?) and the dependency factors that governed the sequence of all the construction activities (when should activities be performed?). However, with limited time available to process comprehensively all aspects of the project information from the contract documents, in order to speedily produce the construction plan, the construction planner normally develops deterministic construction plans based on pure guesswork data (Arditi, 1983; Laufer and Tucker, 1987).

3.5.2 Defining the construction activities

With relevant project information obtained from the main sources as described above, the construction activities for the project could be defined. Arditi (1983) noted that there is much confusion about what should be considered as an adequate degree of detail when developing and representing a construction plan. However, many researchers in planning agreed that the degree of detail to which plans are worked out is a major determinant of construction planning effectiveness (Harrison, 1981; Lichtenberg, 1981: Mason, 1984). Laufer and Tucker (1988) suggested that plans should be prepared at the lowest possible degree of detail at the moment near to the implementation stage as the uncertainty factors become low.

As a general practice, construction activities in the construction plan are normally represented in a varying degree of details. When more detailed plan are prepared, the number and complexity of developing the plan grow rapidly (Kahkonen, 1993). The breakdown of the project construction activities also vary between project to project as well as between construction planners. However, the construction activities normally decomposed or recomposed based on the level of presentation and analysis required from the construction planning process. This process is known as work breakdown structure concept (WBS). For top management, depending on the scale of the construction project, the definition of the construction activities is simplified for presentation purposes as it normally aims to help top management realising the higher goals and means of the project (Ahuja *et al.*, 1994; Laufer & Tucker, 1987).

For a lower level, depending on the level of detail of construction planning required to be performed for controlling and monitoring the project, the presentation is normally elaborated to accommodate clearer solutions of the construction activities for low level managers. The decomposition of the construction activities into lower level also enable correct allocation of resources to the activities (Kartam & Levitt, 1990; Fisher & Aalami, 1996). Furthermore it also enables close monitoring of critical activities rather than the entire construction plan. As a general practice, to provide clearer representation of the construction plan for different levels of project and individuals, the outline of the construction plan is divided into several levels. The level of construction activities presented in the construction plan range from Project, Phases, Zone, Group, Elemental, Work Packages to Task level.

At Project level, the representation would show what projects are undertaken and how they are interrelated over a period of time. At the Phases level, the identification would highlight the integration of several project phases within a single project. This representation is likely to occur on large scale projects which compose of several phases of work. Within a single phase of project representation, the work can be decomposed further to highlight different construction zones which could be presented to distinguish different areas of construction utilising similar construction resources. Figure 3.2 shows the level of representations for which the construction activities can be outlined.

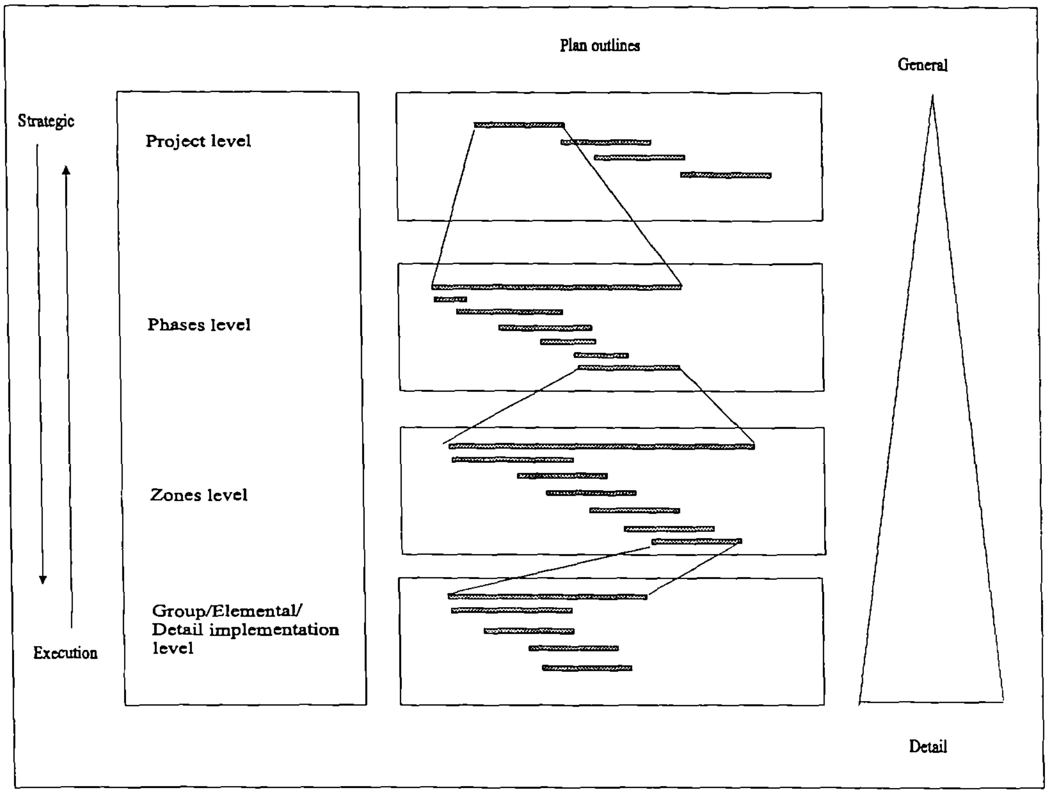


Figure 3.2: The levels of construction plan representation.

For further detailed elaboration, the zones can be represented as various groups of construction works. The groups of construction works would describe the different types of elemental work being planned. Under the elemental work, further decomposition would outline the work packages required to construct the elements and within the workpackages, a task can be elaborated where a single unit or a group of resources can be attached.

3.5.3 Selecting construction methods

In order to calculate the duration and cost estimates for each of the construction activities in the construction plan, most construction planners work with other project participants to select the construction methods required by the various work items in the project. The construction methods would describe the type of resources to be used whether it is in a form of combined resources or just single type of resource. The resources selected would consist of labour, plant and temporary facilities.

Ideally, the selection of a construction method for a particular construction activity required collaborative effort from the construction management team since the factors to be considered vary. and required specific knowledge about the available resources (Cooke, 1992). Various evaluation criteria can be used to select the construction method such as cost, time, suitability, operability, usability, maintainability, etc. For the development of the construction plan, the planner would only be interested in the productivity and the type of resources selected. Nevertheless, the selection of a right construction method is essential and critical for effectiveness and accuracy of the construction plan. In addition, it must also have a significant impact on the duration and cost of the construction activities. Since, not much consideration has been given for identifying alternative construction methods based on systematic evaluation on the construction strategies (Faniran *et al.*,

1994) in a normal practice, the previous project experiences are mostly used, to determine the construction method for most of the construction activities.

The resources type used in a construction method can range from plant, labour, temporary facility to falsework (Illingworth, 1993; Leon, 1971). Each specific resource type needs specific selection criteria. The selection of a specific construction method for a particular construction activity not only requires various knowledge such as productivity, cost, suitability, operability, availability and the used period of the resources for the project, but also involves the time-cost trade-off decision of the construction activities.

Apart from the above factors, variation in design elements also contributed to the selection of the construction method. The planners have to consider the effect of this variation on the selected construction method to avoid delay in the construction operation.

For example, having decided on a construction method based on the operability, suitability, productivity, maintainability, transportability, etc., the construction planner with other appropriate project participants, also has to decide whether using this method (concrete pump method or skip and crane) is providing an acceptable speed and the least cost for construction of a particular building element (concrete work either slab, column, beam or footing).

When variation in design attributes are prominent between these elements, the flexibility and usability of the selected method for the construction activities (e.g. concrete pump method or skip and crane) would become a major consideration besides other factors.

Various types of mathematical models (algorithm) have also been introduced to the industry for the construction management team and the construction planner to decide the trade-off between time and cost which is associated with the construction methods (Liu, 1995; Jaselskis & Ashley, 1991). Although the construction planning effectiveness is subjected by the appropriate determination of construction methods on the basis of a systematic evaluation of the alternatives (Faniran *et al.*, 1994), due to limited time available while formulating the plan, the selection of the construction methods are normally decided merely based on the estimator's recommendation, previous construction records, or the intuition of the planner.

3.5.4 Sequencing the construction activity

Generally, having outlined all the required construction activities and the construction methods for a project, in order to provide a construction plan using project management techniques such as CPM or PERT, the dependency factors for each construction activity represented has to be identified and linked appropriately. Various researchers have addressed the factors that dictate the sequencing of construction activities for a project such as Gray (1986), Benjamin *et al.* (1990), Kartam and Levitt (1990), Zozaya-Gorostiza *et al.*(1989), and Kahkonen (1993). The determination of the construction activities sequence is considered as a major factor for producing an accurate and optimum construction plan. As the lower detail plan is developed, the sequencing of the activities becomes gradually more complex.

In general, the determination of the dependency factors for construction activities requires various knowledge on construction principles, construction regulations, site constraints, resources logistic and project management techniques. The dependency relationships developed between the construction activities would indicate whether the activities are performed in sequence or overlapping.

For some of the dependency factors, they are practically unavoidable while others may be excluded from the construction plan with an increase in construction cost, time effort or risk. Echeverry *et al.* (1991) suggested that sequencing the construction activities is influenced by two types of constraints, i.e. inflexible and flexible. The inflexible constraints refer to conditions which do not allow any modification made on the sequence of the construction activities which may be caused by structural, production technology, safety, regulation, etc. While flexible constraints refer to other constraints which do not impose any restriction on the sequencing of the activities.

When construction planners make decision on the type of dependency between the activities in the construction plan, all the factors that could determine the dependency of the activities have to be taken concurrently into consideration. In normal practice, the creation of the dependency link between the construction activities are based on structural, resources, production technology, environmental constraints, space constraints, regulations and specific preferences (Kahkonen, 1993; Gray, 1986; Kartam & Levitt, 1990; Kartam *et al.,* 1991).

- **Structural**

The dependency made based on structure refer to the concept of physical law where a design element of a building has to be supported by some form of other designed elements. For example, a floor slab is supported by beams and columns. Before the slab can be constructed, the construction of the supporting elements i.e. beams and columns have to be completed. Based on the established elements relationship, the basic structural dependency for the construction activities could be determined.

The critical point in establishing the structure dependency very much depends on the element's relationship with other elements. Some of the relationships which determined the dependency types are connected to, embedded in, supported by, attached to, covered by, etc. Apart from the element relationship, the functional identity of the element also effects the dependency type. For example, if the supporting elements are structural elements, this relationship is primary compared to if the supporting element is an architectural elements or finishes element. Hence when sequencing the construction activities, elements fall under structure relationship (i.e. supported by) are planned ahead than another.

- **Resources**

The dependency established between construction activities based on resources refers to whether or not a resource of a construction activity is shared or reused by other construction activities at different time schedules. Resources in this matter can be of applied or consumable type. The applied type is a resource which is required to facilitate the activity such as labour, plant or temporary facilities while the consumable types are those which are consumed by the activity such as materials and the energy which is required to realise the project.

The critical part in establishing the resources dependency is identifying the construction activities that share the same resources or construction methods. Once they are identified, the dependency could be determined. For example, lifting a formwork and reinforcement bars for a column may use a single crane. Technologically, each of these operations is executed at different times. However, since they share the same crane, the succeeding activity which is lifting the formwork must be linked to the proceeding activity. Equally also, plastering activities on the second floor would depend on completion of plastering activities on the ground floor if the same gang of plasterers is assigned to do the work.

- **Production technology**

Production technology constraint, refers to certain production techniques of construction when applied to realise a design. The production techniques applied would depend on the attributes of the design element. For example a reinforced concrete column requires construction activities such as installation of reinforcement, assemble formwork and concreting to be realised while a steel column requires construction activities such as placing steel columns at its location and placing and tightening the bolt/nut on the steel column base. Each activity from the examples above is carried out in a predefined sequence which is imposed by the construction material and technology of the design element. The sequencing of the required construction activities for these columns would be based on these technological factors.

- **Environmental factors**

Environmental constraints refer to specific environmental matters or conditions that hinder normal sequencing of the construction activities. For example concreting should not be done at raining time unless a temporary roof is provided. Special setup for lighting is required before construction activities can be done at night. Excavation or concreting could not be done until water is pumped out from the ground. When a special construction activity is required, the sequencing of the normal construction activities has to take into account the preconditions and post conditions of any added activity.

- **Space and regulation**

On space and regulation, the dependency is referred as whether the space (work area) or the regulation can impose a constraint on the construction activity, e.g. main road is closed for construction at night and open for public at day time. When space allocation or certain regulations have to be complied with, the conditions which set the constraint to other construction activities has to be included when determining the dependency.

- **Specific preference**

Specific preferences of dependency refers to certain event or time frames where the construction activity can proceed or start, e.g. approval from engineers to execute excavation work, delivery of materials or plant which is specified by the supplier at certain dates in the construction period, etc.

Having established the dependency factors that affect all the construction activities, to provide a complete plan, the construction activities have to be linked based on these factors. The links established between these construction activities creates the construction plan. The common types of link available for developing the construction plan are finish to finish, finish to start, start to finish and start to start. The type of links established between the construction activities indicates the importance of its relationship in the construction plan of the project.

For some types of construction activities, lead and lag time are essentially required before the succeeding or proceeding construction activities could start, e.g. in a concreting activity where lag time is required to allow for the concrete to mature before the succeeding activities are to start, between plastering and painting where the plastering work must be allowed to completely dry before the painting work could proceed. Kahkonen (1993) describes some of the factors which determine the lead and lag time, for the construction activities are the technological processes, the pace of succeeding work, the space constraint, resources sharing and safety procedures.

3.5.5 Resource allocating

Having established the volume of work and the construction method for each construction activity where the type of resources are identified, construction planners have to allocate a suitable number of resources required for each construction activity of the project. Since the number of resources allocated to an activity could influence the effectiveness, time and cost of the construction activity, the appropriate balance of resources are essential. The balance of resources is also important to avoid the discontinuity usage of resources and the lag time.

Resource allocation for construction activities in a network plan can be either limited or unlimited. The limited resources allocation, is performed to asses the impact of the resources to project's duration, while on the unlimited resources the appraisal is conducted to obtain optimal level of resources to achieve a given target of project's duration. Depending on the resources available and the time required to complete the project by the contractors, both limited and unlimited can be used for resources allocation (Ahuja *et al.*. 1994).

In the process of obtaining a balance of the resources for all the construction activities, the construction planners normally make a comparison on the productivity records of a particular construction method. A heuristic approach is applied to determine the appropriate level of resource allocation for each construction activity. However, when the number of construction activities are large and the type of resources vary, resource allocation exercises would only be feasible using a computer system since it can generate faster results for each iteration.

Besides the heuristic approach, a priority list and rules can also be setup for resource allocation to obtain the 'optimal' solution. The priority of the resources is determined according to how important and costly the resources are to the project, and whether the construction activity is a primary or secondary activity. Construction activities which are of a repeated nature, have the highest volume of work and require costly resources are considered as primary activity e.g. concreting, brickwork, steel fixing etc. While activity which is infrequent and has a small volume of work is considered secondary. The primary construction activities would be given the highest priority for resource allocation, since any interruption on these activities would cause severe delay to other construction activities. Furthermore, since the primary activities normally have large volumes of work, discontinuity use of these resources could increase the project cost.

3.5.6 Optimising construction plans

Producing a construction plan with an optimun allocation of resources is the main objective of construction planner. The optimal allocation of resources would allow a constant number of resources being used for the various construction activities to realise the project without jeopardising the project targeted duration and cost. Since in practice, the majority of project have enormous construction activity, the optimisation of resources allocation is normally difficult to achieve (Hendrickson & Au, 1989).

Nevertheless, Ahuja *et al.,*(1994) suggested that 'optimal' solution to resource allocation can only be achieved by mathematical techniques which require many types of analyses and large numbers of iterative processes which can only be performed in a computer system. This application however can only facilitate relatively small numbers of construction activities.

Currently, the optimal procedures that have been developed are divided into two types. They are based on linear programming and enumerative or other mathematical techniques (Ahuja *et al.*, 1994; Karshenas & Haber, 1990). Although both procedures attempt to get 'optimal' solutions by going through all possible solutions and since many variables are involved in resource allocation, these procedures could only be used in small networks where the number of resources and activities are not many.

As a result of this limitation, the heuristic approach which utilises priority rules and procedures are practically being used besides it is the only available means of solving the complex problem in optimising the resource allocation. To obtain the best result, trial and error procedures are employed with different heuristics on the same plan. However, whatever the approach used, one can only attain a planning solution reasonably close to the optimal since planning can easily be affected by enormous factors (Shaked & Warszawaki, 1995).

3.6 The importance of construction planning in a project life cycle

The importance of construction planning to the project life cycle is contributed by the range of information contained by the plan which is essential to support other stages of the project life cycle. Construction plan is referred both at the pre tender and post tender stages by the designer and the construction management team. Currently, the construction plan has been used mainly for two reasons, to support construction management functions (e.g. controlling and monitoring construction activities, estimating, resources management, site layout planning, monthly payment and evaluation, etc.) and recently used to support buildability evaluation of the design.

3.6.1 Supporting construction management functions

Managing site activities requires various functions and operations such as construction planning, site layout planning, resource management, costing, etc. The construction management team who performs these functions normally consists of project manager, quantity surveyor, construction planner, site engineer, purchasing manager, plant manager, etc. Each member of the construction management team has their own roles and contributions to the overall construction process i.e. to plan and organise during the pre tender stage and managing and controlling the construction process at the post tender stage.

At both periods of the construction stages, the construction management team would have to make certain type of analyses and decisions for the construction process. Depending on the function of the construction management team's member, during the setting up period (post tender stage) most of the member would involves primarily in the general planning activities for setting out the requirements for managing the construction process such as, developing construction plan, project cost plan, site layout plan, resources plan, site organisation, setting out plant requirement plan and etc.

Besides referring to the contract documents, drawings, bill of quantities, specifications and etc. to provide the general information of the project, the construction team normally refer to construction plans to act as a medium for arriving at common solutions of the construction approach prior to the construction stage and as a source of reference that contain construction information and guidelines about the execution of construction activities for the project at later stage. Figure 3.2 illustrate the use of construction plan in construction.

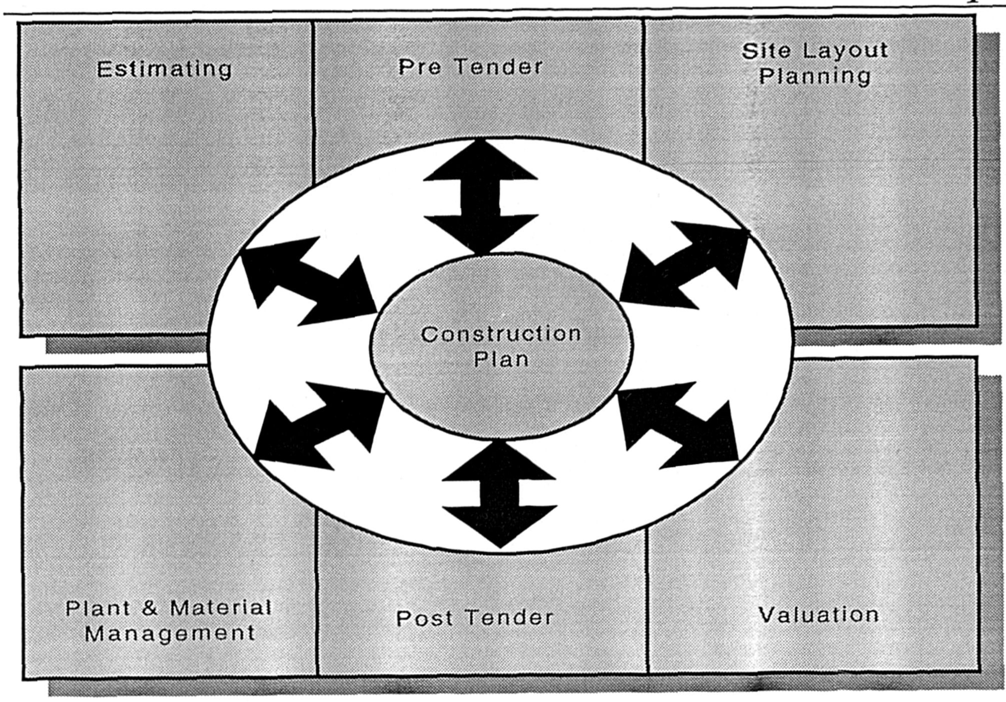


Figure 3.2 The use of construction plan

At pre tender stage, while the construction planning is at its very early development stage as it is still being under collective reviews and consultation by the construction management team to derive at the final solution, the initial construction plan provides the means for:-

- Determine suitable type of plant for the construction activities: To determine suitable plant for the construction activities, simultaneous analysis of ground condition, site layout and cost are required. The site engineer would require to know the type of plant and facilities associated with the construction activities in order to decide the appropriate plant and facilities throughout the construction period of the project. The type, date start, the date finish of the construction activities would indicate when the plants and facilities are required on site. Having these information at the early stage would facilitate the site engineer to analyse systematically and determine the suitable plant or facilities within the constraint imposed by the site.

- Assess the impacts of the construction methods:- To obtain the least cost or duration for various type of construction activities by examining various construction methods that are available and suitable for the project would have to be evaluated in the construction plan.

- Establish materials procurements and delivery date:- The work content of each construction activities and the whole construction plan would be able to highlight the amount and type of materials required on site at a particular time. Advantages on the procurement strategies may influence the sequence of the construction activities on the initial construction plan.

- Determine the date for the required plants:- The availability and suitability of the plant for the construction activities may influence the initial construction method and sequence of the construction activities.

- Establish the construction cost:- The construction methods, construction resources, duration and sequence of the construction activities used in the construction plan effects the construction cost.

- Allocate budget for the operation on site:- The agreed construction plan also would allow the estimator to prepare the cost budget at certain time interval, for each type of construction activity that would be performed on site.

- Decide required detail drawings and specifications:- If detail design is not available for some of the construction activities at the early development stage of the construction plan, specific information either in the form of detail drawing or specifications could be requested and highlighted in the construction plan.

- Assess the space constraints for the construction activities and its methods:- The initial construction plan provided could be used to assess the space constraints in relation to the construction methods employ for the construction activities. The data from the construction plan which indicate the time and method of construction would be evaluated with the availability of site space as the construction progress. The space constraints may influence the selection of the construction methods thus the overall construction plan.

However, once the final solutions for the construction plan are agreed, at the post construction stage, the construction plan would provide the basic references for construction planner as well as other participants of the project to :-

- Track progress of work on site:- To compare what has been planned, what has been achieved, what is going to be done next and to rectify any deviation of the construction activities to the original construction plan.

- Produce monthly or weekly progress report:- It would highlight any form of construction activities or general events that may have influence the efficiency and effectiveness of the construction plan.

- Establish resources schedules:- Under resources management, various resources such as plants, labour, temporary facilities, material have to be managed and allocated as when it is necessary. Each type of resources have significant effects on the formulation of construction plan. The construction plan provides the main data to support the resources management to develop the resources schedules. Information such as the type of construction activity. the date start and finish, the type and quantity of resources required would help resources manager to schedule the time table for deliveries of the resources and decide the method of procurement between the suppliers and site preparations to store the material temporarily can be outlined accordingly with the construction activities on site.

- Determine labour schedules:- Labour types and requirements for each activities can be determined in advance and the necessary preparation can be made prior to the start of the work.

- Ascertain the request and inspection date for local authority:- Important dates for inspection by the local authorities could be made in advance prior to the start of the construction activities.

- Establish start date for various subcontractors:- Construction activities which are to be executed by the subcontractor can be presented as early as possible to secure their commitment.

- Compare incurred construction cost with planned cost:- As the construction work progress, the construction management team would be able to analyse the actual construction cost with the planned cost. Adjustments and necessary actions could be taken from the evaluation.

- Prepare the project evaluation and monthly payments:- The monthly payments received by the contractor from the client are determined by measuring the cost of current completed construction activities from previous made claim. The construction plan produced for the project normally is accepted by the client as an agreed guideline on how the constructor would build the project. To support the claims for the payment, the construction plan which highlights the planned and the progress made on the construction activities would be presented as an evidence that construction activities required to construct the project has been done besides the actual measurement of the completed works conducted on site.

- Solve project or construction disputes arrived from various interference:- Any dispute over the delay of the project caused by various interference such as weather, strike, redesigned work, late deliveries of materials or unavailability of labour, etc. can be analysed from comparing the recorded actual construction plan and the initial construction plan besides the site diary and other reports.

- Requesting extension of time if project is overrun:- Based on the progress of work marked on the construction plan and with other interference noted in the construction plan can be used to support extension of time.

3.6.2 Supporting buildability evaluation

Various researchers have suggested that, by formalising the construction planning process, the produced construction plan can be used as a prediction tool to reflect the construction time and costs required to realise the project and the buildability aspects of the design (Stretton & Steven,1989; Gray, 1986; Yau, 1992; Moore, 1996). Planning information such as construction activities, resources, time and cost can be formalised and used to evaluate the buildability of the design.

Since designers do not often examine the impact of their design on construction, it is important to develop an evaluation method to check on buildability aspects before actual construction work proceeds. Since construction planning processes produce the majority of the project construction data in the construction plan, an evaluation approach for buildability of the design would become feasible, Figure 3.3.

Depending on the construction activities aggregation developed in the construction plan, information such as the type of activities, the process sequences, the construction methods, the required resources, and the cost associated with the specific design elements, could be used as a measurement for buildability. This information can be used by the designer to choose other alternative design options which are more buildable. It can also highlight any design element and it's construction attributes which has a 'bad' effect on the buildability.

Using the construction plan, the aspects of buildability which can be analysed are the repetitiveness or standardisation of the construction process or work packages (Gray, 1986), the effect of element geometrical properties on the resources requirements (Fischer, 1991), the effect of specifications on the construction method, and the effect of complicated or simplified design detailing on the construction duration (Jergeas, 1989), the effect of design on cranes selection on site, etc.

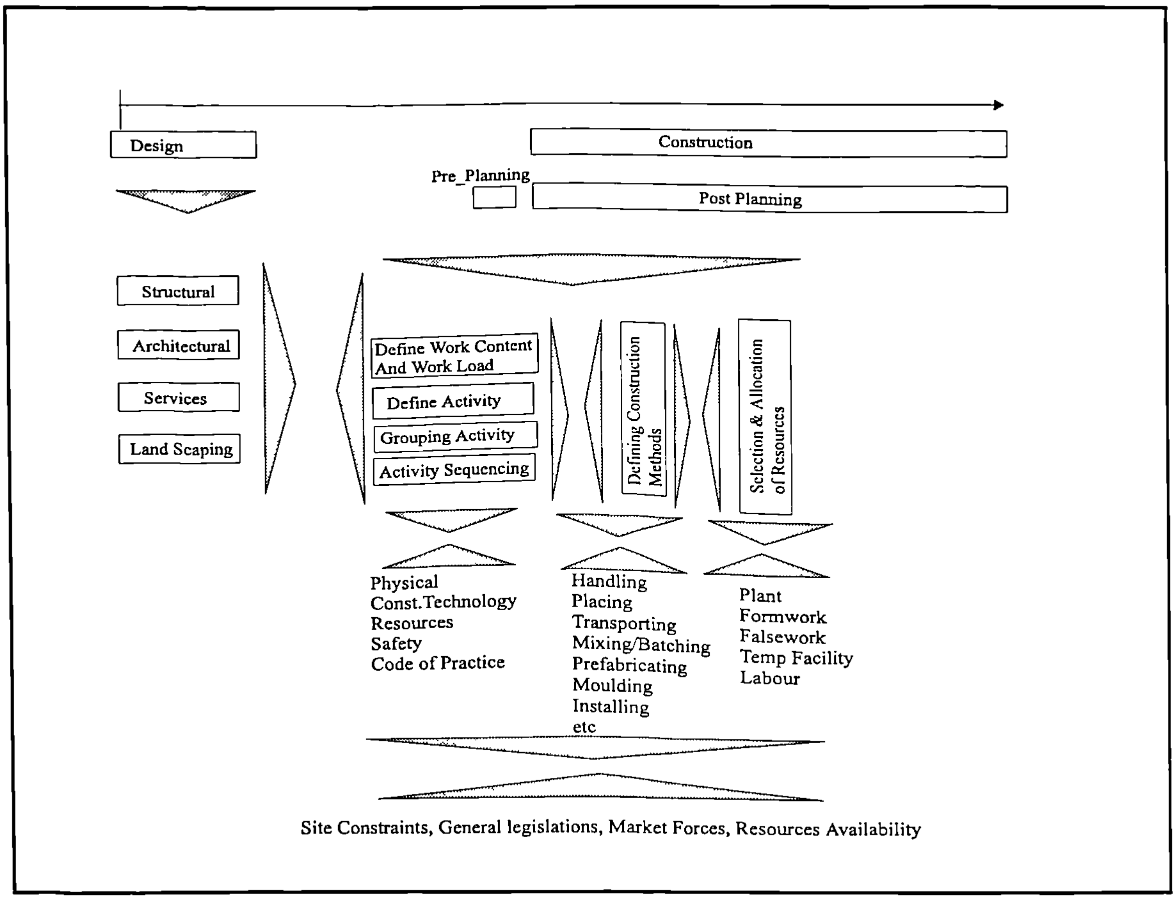


Figure 3.3 The relationship between design and construction information in construction planning

The construction plan could also be used to analyse any design element which breaks the rhythm of the erection cycle which could result in the increase of non-productive time, or reducing the speed of overall construction activities (Illingworth, 1984).

3.7 Summary

This chapter has highlighted the aspects of construction planning, its main processes and the contributions of the process to the construction industry. The overview has decsribed the importance aspects of the process in supporting the project life cycle and the problems of generating the construction plan. To provide an overview of the developed applications for this domain, the following chapter will outline some of the construction planning and buildability assesement applications.

Chapter 4
Construction Planning and Buildability Assessment: The Current Systems

4.1 Introduction

Realising the potential advantages of good buildability projects, a gradual number of research organisations from various countries such as USA, UK, Australia have been involved to obtain more clear understanding of the subject. As a result, numerous guidelines and recommendations have been produced for the construction industry. Some of the outlined principles founded which can improve buildability aspects in the construction industry are construction driven design, standardisation, repetitiveness, simplicity of design, effective communication system, concurrent engineering, etc. (O'Connor *et al.*,1986; CIRIA, 1983; Hon *et al.*, 1989).

Although various buildability principles have been outlined to improve the whole aspect of project development in the construction industry, only a few of the outlined principles are possible, to be implemented directly when the design is formulated while others need a new methodical approach of evaluation. Construction planning process was initially formalised as an effort to provide the requirement for the evaluation since it provides the construction cost and duration of the project (Stretton & Steven, 1989; Gray, 1986). However, various factors have been identified obstructing the full implementation of buildability principles in the project development using construction information. The major causes are such as the existing separation of the design and construction which prevents exchanging or sharing of construction information to validate the design, the current practice of procurement system and the need of the buildability evaluation for interdisciplinary collaborations (Kalay, 1991; Underwood, 1995; Moore, 1996; Fisher & Aalami, 1994)

Since the majority of the research works mainly concentrating on producing the theoretical frameworks to buildability, there is little progress made to provide quantitative computational design analyses of buildability where designers can use the principles to evaluate their design (Fisher & Aalami, 1994; Moore, 1996). Since one of the aims of this research is to formalise construction planning processes for buildability evaluation and incorporate both domains of construction planning and buildability as a single application, the reviews in this chapter will highlight the various research efforts on the developed prototype systems covering construction planning applications and buildability applications. The aims and objectives of each of these research works, their prototype system architecture, the proposed evaluation method, and the system limitation would be discussed.

4.2 Computer application systems for construction planning

The construction planning process which produces construction plans and their related construction information is normally part of the function which is performed by the contractor to manage the site operation during the construction stage. However, with the current influence of information technology where construction planning analysis can be produced quickly and reliably, the use of construction planning gradually becomes essential for every aspect of design such as design assessment (Stretton & Steven, 1989; Gray, 1986; Yamazaki, 1993), construction simulation (Morad & Beliveau, 1989 & 1991), buildability evaluation (Fisher & Aalami, 1994; Fisher *et al.*, 1995), and construction management, such as estimating (Yau *et al.*,1991, Nevins & Zabilski, 1991), resources management (Shtub, 1988), progress payments and monthly evaluation (Abudayyeh & Rasdorf, 1991; Alshawi & Underwood, 1996) and construction process evaluations (Moore, 1996 .

The introduction of computer systems in construction planning gradually developed since the 1960s. A few big construction companies at the time employed their own in-house computer systems to execute some of the construction planning task. The critical path analysis and other similar project network techniques laid down the milestones for using the computer in construction planning (Levitt & Kunz, 1985). The use of computer systems in construction planning has eliminated most of the tedious processes in developing and presenting a construction plan. As computer hardware and software becomes relatively cheap, the computer systems for construction planning application has been widely used and indispensable as aids in developing a construction plan.

The existing project management computer systems have greatly facilitated the efficiency of the CPM and PERT techniques. They provide support for both scheduling by performing network computation dates, resources and cost reporting by data base management systems (Dym & Levitt, 1991). Although, project management computer systems have reduced a considerable amount of tedious work on construction planners and was capable of generating quick and reliable CPM and PERT for a project plan, the application still depends highly upon a knowledgeable construction planner to examine and interpret the design, develop the solution of the plan and derive with the meaningful input data for the application system (Levitt *et al.,* 1988; Alshawi & Hassan, 1994). In addition, the data generated by the construction planner for the planning system still has to be laboriously input into the computer system. Although at the time the project management computer system could effectively automate project schedules and resources allocations however, most of the systems do not support project decision making.

Nevertheless, the continuos research development has improved this tedious operation and limitations of the project management system, by incorporating the knowledge bases system and graphical applications, which assists in the basic decision making process for generating the plan. Various researchers have provided the reviews and the prototypes describing the development of their integrated system such as Tate (1985), Levitt & Kunz (1987), Zozaya-Gorostiza *et al.* (1989), Kartam *et al.* (1991), Alshawi *et al.* (1990), Yamazaki (1991), etc. Later, the adaptation of advances in the information technology have not only assisted the process but also increased the general contributions of the construction planning process from merely automating project schedules and resource allocations to provide quicker and reliable construction plans into supporting project decision making.

The first attempt to automation of the construction planning process was done using rule base systems with the project management application system. The incorporation of the rule base systems have automated most of the decision making factors on the construction planing process (Zozaya-Gorostiza *et al.*, 1989; Alshawi & Jagger, 1991). Simultaneously also, various diverted efforts were conducted to integrate design data with knowledge based systems to generate construction plans (Darwiche *et al.*, 1989; Cherneff *et al.*, 1991; Aouad, 1991; Alshawi & Hassan, 1994, Tah *et al.*, 1994, Kartam, 1994). This move has improved efficiency of data communication and reduced further the amount of work required by the construction planner to interpret design and project data. Although not all information from design data is automatically interpreted, this integration eliminated some of the laborious information gathering tasks required to be done at initial stages of construction planning.

Another research work which utilises construction plans was to produce construction simulation. The simulation of the construction process was displayed on a graphical interface based on construction planning (Simon, *et al.*, 1988, McCahill & Bernold, 1989). This research work provided new facilities for construction planners and the designers to evaluate the construction process. Moreover, since cost estimates are required to supply the cost data for the construction planning, other researchers have worked out the integration of estimating with construction planning and design (Yau, 1992; Underwood& Alshawi,1996).

Since buildability concepts awareness emerged, the construction plan which highlights the 'what' resources are being used, 'how' the activity is been executed, at 'what' cost and on 'what' duration is it required has been formalised as construction driven design assessment (O'Connor *et al.*, 1986; Gray, 1986; Stretton & Steven, 1989). The construction planning process which produced the related construction information has been adopted in the design stage for evaluating the design. The adoption of construction planning process knowledge during design stage provides useful feedback to designers on the impact of their design on construction. Designers would be able to evaluate their design more effectively based on the construction cost, duration, construction process, and resources required. The impact of any changes made at this stage can be examined on the design without significantly increased project cost as compared to alterations made during the construction stage or later stage of the project life cycle.

Below are a few examples of the previous research on construction planning process in the construction industry.

4.2.1 BUILDER (Generation of Schedules from Drawings)

BUILDER (Cherneff, 1988) is a prototype system which is developed in M.I.T. to incorporate design and construction. The research is conducted to resolve problems in the separation of design and construction processes. It is assumed that by generating the construction plan at design stage, the designers would be able to reflect their design decision on construction.

Aims and objectives of the research

BUILDER aims to provide designers with a real time construction plan which shows both schedule and cost to realise the facility. It also intended to implicitly reflect equipment requirements, productivity and buildability of the design.

System architecture

The BUILDER (Cherneff, 1988) consists of two knowledge bases, namely for drawing creation/interpretation and construction scheduling. It has been successfully used to automate construction planning from a drawing. The knowledge base called DRAW can identify objects such as wall and assign appropriate attributes. All objects from drawings are stored in a semantic network representation linked with a variety of relationships, from IS-A for a simple inheritance to connected-to, part-of, bounded-by, etc.

PLANNER the second knowledge bases of BUILDER is organised around building components. A task is created from every drawn component which later produces the construction activities. BUILDER uses bottom up approach to create an activity sequence. It operates in four steps; identifying the drawn object, separating construction component from others, creating an activity network and lastly producing a crude bar chart for the project. The system interacts CAD (for description of building components as the main form of input data) with a knowledge base system and database to generate a project network.

System limitations

Although, BUILDER has been successfully developed through integration as a knowledge base system for generating construction schedules, there are a few areas of construction planning that the system does not cover. The system does not address variable crew sizes or resource limitations for each activity therefore a resources levelling facility is not available. The graphical presentation of the project network produced by BUILDER is relatively poor as the system does not link with other planning tools where the advantages of the system to perform network analysis can be utilised. For buildability aspects, there is no intention yet made by the researcher to adopt the system for buildability evaluation in design.

4.2.2 PLATFORM

PLATFORM was developed at Stanford University (Levitt & Kunz, 1985). The focus of the research work was to identify the risks which can affect the performance of the construction project up to a certain point and use them to forecast the duration of the remaining activities.

Aims and objectives of the research

PLATFORM (Levitt & Kunz, 1985) is developed to update activity plans for the construction of off-shore platforms. The purpose of the program is to update the plan by altering either their attributes, such as duration or dependency in response to reports of the actual duration of activities accomplished. The system reasons about trends and interrelationships in the plan. The plan dependency alteration is created by selecting from the predefined alternate sub networks for major activities.

System architecture

The system is essentially a knowledge base project-reporting system. The basic principle of PLATFORM's knowledge base is to capture the logic of the scheduling process and make it available to a rule base system for project updating. The system was implemented using IntelliCorp's KEE which is a hybrid rule/frame/object-oriented programming development tool with LISP as the underlying language.

System limitations

Although the system has been developed to produce reports on the project rather than generating a project plan, the system is being updated to be linked with a CAD system and a knowledge base planning program (Ito *et al.,* 1989; Kartam *et al.*,1991). Since PLATFORM was developed, continuous enhancements were made to include new facilities to the system such as interactive scheduling system (GNATT) and capability of making feasibility decisions under uncertainty. As part of updating process, PLATFORM III is now a latest version of the system

4.2.3 CONSTRUCTION-PLANEX

CONSTRUCTION-PLANEX was initially developed in 1987 by the researchers at Carnegie Mellon University (Zozaya-Gorostiza *et al.*,1989). The initial work was aimed at providing a construction plan for excavation works but later was directed toward the erection of building structures. CONSTRUCTION-PLANEX is an implementation of PLANEX which is primarily based on the non linear planning paradigm developed in an artificial intelligence.

Aims and objectives of the research

The succeeding research work was intended to provide a method to generate activity plans for concrete or steel frame building. CONSTRUCTION-PLANEX (Hendrickson *et al.*, 1987) is developed as part of the research work to enable the generating of construction plans for excavation works and structural erection of concrete and steel framed buildings.

System architecture

The system is a stand alone knowledge base planning system which has been implemented using Common LISP and Knowledge Craft. The system architecture consists of a context of the problem (working memory to store the known information describing the current problem). operators (to operate on the information in the context) and knowledge sources. The program is slightly different from other knowledge based planning systems as it suggests technologies besides generating activities, determines precedence. estimates duration and develops the schedule.

The program's knowledge base contains a large number of knowledge sources to perform technology choice, duration estimation, precedence setting and activity identification for office building projects. The knowledge source is tabulated in the form of a decision table which transfers the knowledge into a network of frame schema. The system provides the capability of backtracking of previous decisions and also provides the user with information about the outcomes of particular task.

CONSTRUCTION-PLANEX requires input such as the specification of the physical elements in the design, site information and resource availability before transferring the information into a complete construction plan with a provisional schedule and cost estimates.

System limitations

The main drawbacks of CONSTRUCTION-PLANEX compared to other systems is that it does not link with any type of CAD system. The user has to input geometric information about every design element of a building before the system can provide a textual project activity plan, estimated duration, cost estimates and schedules, including the definition of activities, specification of precedence, selection of appropriate technology for the task. The process of inputting data is described as cumbersome. The application of CONSTRUCTION-PLANEX is only limited to plan modular high-rise buildings, including excavation, foundation and structural construction. CONSTRUCTION-PLANEX provides reports on graphical presentation GANTT (interactive scheduler) to simplify the project plan. The system also provides the following output graphics;

- Activity-on-node diagrams which display project activity network
- Cost curve

- Cumulative cost curve
- Animation program which displays the status of the building at various points of project execution

As part of the future plan for the system, it is likely that CONSTRUCTION-PLANEX will create a communication link with a CAD system. Since CONSTRUCTION-PLANEX is still under continuous development, the use of the construction information generated from the system for buildability evaluation is not yet part of the system development.

4.2.4 GHOST

The system was developed by a group of researchers at the Carnegie-Mellon University and the Massachusetts Institute of Technology (Dym & Levitt, 1991; Navinchandra *et al.*, 1988).

Aims and objective of the research

The primary aim of GHOST (Generator of Hierarchical networks for cOnSTruction) is to use the knowledge sources built in the system to critique the project plan. GHOST takes input such as project construction drawings, material specifications, resources availability, and lead times, for acquiring different materials, availability of trades and project personnel and knowledge about past approaches to similar projects. Among the type of critics used by GHOST are about physical laws when developing a construction plan (e.g. walls/columns must be built before roof), about construction process, inheritance and refinement critics, and checking on the redundancy. The critics are applied to a set of construction activities supplied by the user to check the order of the network. Therefore, the program only produces output of project plan optimised by trade, resources and costs, assigns duration and expectations to the activities and plan analysis.

System architecture

GHOST is an integrated knowledge based environment for construction planning (Navinchandra *et al.*, 1988). The system is part of a larger integrated knowledge based system called CONPLAN. The control structure in GHOST involves a simple blackboard architecture that reasons about applying the critics.

System limitations

The setback of the GHOST system is that the system is part of larger integrated knowledge based system for construction planning called CONPLAN. Therefore, the system requires manual input from users. The system functions as a criticiser in order to produce a better optimised project plan. Further research work is still being carried out to extend GHOST's knowledge base, as to include scheduling the different trades (e.g. carpenters, bricklayer, etc.) for optimally, estimating activity duration and improving the structure. The system is unable to produce good graphical plans therefore the developer intends to integrate with powerful project management software. Since GHOST 's intention is to critique a project construction activities plan to obtain efficient and effective plan, the information available from the project plan is not being utilised to criticise the design solution for buildability.

4.2.5 OARPLAN

OARPLAN (Object-Action-Resource-Planning) was developed at the Centre for Integrated Facility Engineering (CIFE) of the Stanford University in 1989 (Darwiche *et al.*,1989).

Aims and objectives of the research

The system aims to combine the general purpose planning system and domain specific expert planning systems. OARPLAN produces construction project plans from a description of the objects that represent the facility. It uses models of product and project structure and functions as part of its reasoning.

The generation of construction plans in the system is dependent on the supply of extensive information about construction objects, actions, resources, spatial and topological relationships, that may exist between the objects. This information is stored in a knowledge source. Among the information required by OARPLAN are the components classes, e.g., floors, beams, columns etc., components properties, e.g., dimensions, materials, finishes, etc., components geometric and topological relationships, e.g. , supported by, enclosed by, adjacent to, etc.

System architecture

OARPLAN was implemented using the BB1 blackboard environment running under Common LISP on a TI Explorer workstation (BB1, a system organised as a set of blackboards, each having its own function. was developed in the Knowledge System Laboratory at Stanford University). To produce the construction plan in OARPLAN, the user would have to describe his/her facility by designing the building in AutoCAD. Using CIFECAD as an interface, the information about the facility is passed on to a rule base system to generate a plan.

System limitations

OARPLAN generates a plan from a high level to the lowest level of activity, e.g. from Build Building to finer levels of detail such as Place Concrete. It uses different knowledge sources to elaborate each activity and creating its dependency. The activities are elaborated until no more knowledge sources are applicable. Each activity in OARPLAN is defined in term of its three components i.e. Action, Object and Resources.

Although, OARPLAN could generate the construction plan for a project in an integrated approach, at present as it is an on-going project at Stanford University, work is undertaken to incorporate the resources component while defining an activity and also to utilise the interaction of the resources component of different activities while determining their precedence (Dym & Levitt, 1991). Although, OARPLAN produces the constructional data of the project, the information produced from the system is not yet being utilised to support buildability evaluation.

4.3 Computer application systems for buildability assessments

The brief produced at the early stage of the project life cycle which highlights the parameters of cost, time, quality, facility function and specifies the contractual aspects and applicable agreements would be used by designers to derive precisely what is needed for the project and how it can be achieved. As the design work progresses through its conceptual, preliminary design and the final detailed design phases, and since design requires multidisciplinary analysis, various aspects of the design project such as structural, cost, services, quality etc. would be evaluated from different perspectives of project participants in order to converge with the client's brief.

During assessing their design, the designers normally refer to the published technical information, the responsible party in the project team, their design experiences of a particular design problem and previous records of design. Since design influences various project aspects such as functions, performance, aesthetic, cost and buildability, to obtain optimum project design, an integrated evaluation methods would be required to be performed on these aspects (Kalay, 1991). The evaluation for buildability of a design ideally should be performed as early as possible during design stage and as the design is progressed.

As computer technology becomes more apparent and sophisticated especially the Artificial Intelligent (AI) systems, many aspects of the design evaluations are inclined to be automated including buildability. Below are some of the prototype systems developed by previous researchers to assess the buildability of a project.

4.3.1 PREDICTE

PREDICTE (Project Early Design-stage Indicative Construction Time Estimate) is a research work which was conducted at University of Sidney in Australia (Stretton & Steven, 1989). An expert system for assessing buildability was developed from the study which emphasises the owner/user perspective i.e. reflecting the project time.

Aims and objectives of the research work

The research work was set to provide a computer evaluation technique that could improve early concepts of the design using construction time as a criterion when little information of the project is available. To achieve this aim, an expert system was developed for this purpose to predict the construction time estimate for concrete framed multi-storey buildings.

System architecture

The expert system was built using a representation language called Candle, which was specifically developed by Digital Equipment Co-operation (DEC) for the project. The expert system architecture comprised of three elements, the user interface, the knowledge base and, the inference engine. The user interface is used to obtain the project information through structured questions and sketches of the building. The knowledge base is designed to assess a realistic construction time for the proposed scheme, to analyse the concept for opportunities and test alternatives, explain any part of the assessment and present a documented report and bar chart. The inference engine function is to ask the questions and generating the information required by the system to derive with the recommended solutions.

Evaluation methods

In an interactive manner, based on some questions and the answers provided by the users, the expert system prepares recommendations as well as performing the assessment for a realistic construction time on existing schemes. About 223 questions are designed in PREDICTE, however, depending on the configuration of the building. ground condition and the likes, between 100-140 questions would normally be required to be answered. Upon completing the assessment, the system would be able explain any part of the assessment and present a documented report and bar-chart that could be used for a submission, or for estimates of cash-flow or time-based costs.

System limitations

PREDICTE is designed to assess projects at early stages in order to produce a construction time indication of the project. The system was among the earliest expert systems being implemented for this purpose. Since PREDICTE is built as a single application system, its usage is limited to the early design concept which only applied general rules to derive the time frame of the project. Many other aspects of buildability such as suitability of a selected method for construction work. costs comparisons, the profile and pattern of resources required, dimensional tolerances. model of the construction processes could not be performed by the system. The expert system shell used by PERDICTE prevents the system from being integrated with database systems, project management systems and CAD.

4.3.2 'Intelligent' construction time and cost analysis

The research work was presented by Gray (1986) at University of Reading to prove the hypothesis that the majority of construction activities can be selected from a set of rules governing the construction works which is originated from design objects.

Aims and objectives of the research work

To provide designers with a knowledge based system which evaluates design from a construction process model which is normally employed by contractors. The assessment indicates the cost and the time required to build a particular design. In order to outline the rules which govern the generation and allocation of the construction activity, Gray (1986) studied the various ways in which construction planners established their construction activity.

The studies were later used to provide the knowledge database to evaluate the design and to structure the analytical rules that determine the construction activity, cost and time.

System architecture

The Intelligent Knowledge Based System (IKBS) is developed using PROLOG language. The IKBS contains three parts, the user interface. the knowledge base and the inference engine. The user interface comprises mostly the questions needed to generate the assessment (i.e. about the building design) and the format for report output. The knowledge base contains production rules about different kinds of construction systems and their components.

These production rules would enable the system to define the building model and the choices of construction technology made for the construction activities. The knowledge base also contains general and heuristic rules for defining activity duration and their relationships. The inference engine generates the questions and uses the input provided by the user to find and build the required plan of activities upon which the specific time and cost analysis is calculated.

Evaluation methods

To perform the assessment, the user has to answer a series of questions about the building design such as the size of building, type of constructions and crane requirements for the project. Once the initial questions are answered IKBS seeks details of the type of construction through presenting a series of options at key decision points to quickly obtain the greater precision of the assessment. The output of the assessments is the construction programme which indicates the required construction activity, its duration and relationship with other activities, the expenses and time taken by the staff and plant, and the site accommodation cost. The result also indicates the level of resources demanded such as trade, the material and plant required, and the amount of the work volume. The user has to evaluate their design from the produced cost and time scale from the assessment.

System limitations

The IKBS programme incorporates various practices of many planners to produce a realistic forecast of the time and cost for the design. Since the system is operated on a single knowledge based system, to evaluate the scale of time and cost imply on the design, the user has to input various project data in response to a number of questions.

The result of the buildability assessment indicates the general implication of the design through the use of construction resources, cost and time which are associated with the required construction activity. Since the implication of the design in IKBS is represented by general construction activities such as foundation, ground floor slab, plaster ceiling, roof slab, concrete 1st floor, etc., further analysis is needed to find out what the specific construction works which induce greater buildability problems i.e. whether it caused by conversion of material to form the building element i.e. concreting, formwork, transportation or by the process of assembly, the specification of the elements, the orientation of the building elements components, irregular design and shape, etc.

Since all the results of the assessments are presented in textual format and on a bar chart, where there is no indication on which building element or construction process (i.e. assembly of formwork, concreting, assembly reinforcement, transportation of the materials and etc.) accrues the problem, the designer could not possibly identify the element of the design efficiently from the analysis. In order to highlight the specific construction processes which may effect buildability, the construction activity represented in IKBS has to be aggregated to the lowest level of abstraction.

Furthermore, to establish which building element induces the buildability problem, the construction activity presented in IKBS has to clearly indicate its link to the building elements.

4.3.3 COKE

COKE (Construction Knowledge Expert) is a prototype system developed from a research work conducted at the Center for Integrated Facility Engineering (CIFE) at Stanford University, USA (Fisher, 1991). The prototype system is a result of formalising and representing buildability knowledge, development of product model and integration of the knowledge with the product model.

Aims and objectives of the research work

COKE is developed to provide designers with buildability feedback for the layout and dimensioning of reinforced concrete framed structures in relation to a formwork system. The assessment evaluates the constraint imposed by various construction methods of formwork and provides solutions and recommendations to designers at the early stage of the structure design.

System architecture

COKE used AutoCAD for graphical interface and KAPPA-PC as the experts system shell. Since COKE`s operation relies only on the data available from CAD systems, specific functions retrieving specific project data at the appropriate level of detail are required for reasoning about buildability.

The menus and functions in AutoCAD which is programmed in AutoLISP make the AutoCAD an object based CAD system that could capture the project data necessary for buildability assessment. The menu-functions were customised to allow designer to model their structure elements and their relationship in 3D. Project data is saved as ASCII file which later used by COKE to evaluate the buildability factors.

System evaluation

COKE can be operated, once the designed structure has been drawn on a CAD system. Data from the CAD system is first interpreted into an ASCII file. The functions created in KAPPA-PC read the ASCII that contains the specific project information and stores the appropriate information in the developed product model where the buildability reasoning is structured. Based on the reasoning developed in the knowledge based system. the project data stored in the product model is compared with the buildability knowledge where feedback is supplied to the designer. When a construction method was not specified, the system automatically selects construction methods which are applicable for the structure.

In order to assess the structure for the suitable formwork system, the knowledge base system applies three types of constructability reasoning. namely the reasoning about the attributes of the objects. reasoning about the relationships between attributes of the objects, and spatial reasoning. When reasoning about the attributes of the object, the assessment only uses an attribute value of a structural element and comparing it to the appropriate value from the knowledge base. Reasoning about the relationship between attributes is performed by taking the attribute of an object and propagating its influence on attributes of a different object. The spatial reasoning is done by generating the necessary data to form a geometrical and topological information of the product model which is then used to analyse the constructability of the structure.

System limitations

COKE was designed to provide reasoning for buildability about construction methods, mainly associated with formwork systems to the structural elements. The user is advised whether a selected construction method for the structural elements would ease the construction work or otherwise. If the user did not specify any construction method, then the system will use the general project information and application heuristic to dismiss certain construction methods which are not applicable for the structure.

Since the buildability assessment focuses only on construction methods of a formwork system, various other factors which could affect buildability such as, the related construction activity processes. site factor, labour requirement, plant requirement etc. could not be accounted for in the analysis. Moreover, as it works independently from other aspects of buildability views, the system could not provide an 'optimum' design solution rather than just sub-optimising a single solution factor of buildability.

Although the result of optimising a single factor of buildability is beneficial. the solution put forward by the system does not reflect an optimum design approach as other factors are not addressed.

4.3.4 The Dimensional Bay Design System

This research work was conducted in 1995 at University of Salford (Alshawi & Underwood, 1996), mainly to identify and solve the buildability problem related to dimensional tolerances in design. A prototype application system called The Dimensional Bay Design System has been produced as a result of this research.

Aims and objectives of the research work

The aim of the research is to improve buildability of design solutions based upon the analysis on information related to site problems and the design process. The study led to a development of a prototype system which addresses the buildability problem of dimensional tolerances between the horizontal/vertical layout of structure elements and cladding and lining systems.

System architecture

The Dimensional Bay Design System was built as a single application that contains graphical user interface. An object oriented development environment tool KEE (Knowledge Engineering Environment) was used to develop the reasoning and the mechanisms of the system evaluation while

ORACLE RDBMS was implemented for the creation of a database of standard cladding and lining elements.

Since KEE could not directly access the database in ORACLE, to provide the means for communication of data between ORACLE and KEE, functions were written in Lucid's Common LISP and C languages. The application system runs on Sun SPARC workstation (Underwood, 1995).

Evaluation methods

Based on a project specific information, the system provides various cladding systems which are roughly appropriate for the horizontal/vertical layout of the designed structure elements. Once the user has selected the required cladding type, the system matches the lining type for the cladding. The system also accordingly adjusts the grid layout, the floor to ceiling height, and sizing of columns and beams, to correspond with the selected cladding and lining type.

In order to obtain optimum lining element for each cladding when sizing and adjusting the structure orientation, the least volume of concrete for the frame elements principle is used. Once the optimum solution is available, other options are dismissed and the result is presented in a two dimensional graphical image.

System limitations

The Dimensional Bay Design System is developed to solve dimensional tolerances between a cladding system with the layout of the horizontal and vertical structure elements through a knowledge based system and a database system. The Dimensional Bay Design System solution identifies the suitable cladding type and the dimensional requirement for the horizontal/vertical structure elements.

Since the system only assesses dimensional tolerance between a cladding system with the layout of the horizontal and vertical structure elements, many other buildability factors such as, the construction processes. site factor, labour requirement, plant requirement, etc. are not addressed. Therefore, the system does not produce 'optimum' design solutions rather than sub-optimising a single factor of buildability elements. Although the result of optimising a single factor of buildability is valuable, since design solution is interdependent on other variables, the solution put forward by the system does not reflect an optimum design approach.

4.3.5 CADDS

The research work was carried out to establish buildability which associated with design detailing. The initial work was set by Jergeas (1989) at University of Loughborough, U.K. and was later implemented at Concordia University, Montreal, Quebec, Canada by Alkass *et al.*. (1991).

Aims and objectives of the research work

Based on the initial studies, the development of the system aimed to assist architects and structural engineers in selecting the most appropriate and easy way to construct design details for concrete structures. The study recognised that little effort has been made by designers to catalogue various options of construction details and their effects to buildability.

Using computer technology to store and classify field experiences, CADDS (Constructability Assessment for a Design Detail System) is developed to present the combination of data and knowledge gained from experience in design and construction to solve this particular problem.

System architecture

The CADDS system architecture consists of four elements, i.e. Graphical Data base module, Cost Data Base Module, Detail Properties Module and the Knowledge base Module. A graphical data base module is used to store different wall system details; the cost data base module is designed to compute the cost of labour, materials and equipment; the detail properties module containing the detail components, attachment, advantages and disadvantages and usage constraint of the wall system, and finally the knowledge base module, where the rules and mechanisms for evaluating the wall system are built.

Evaluation methods

CADDS evaluation process is executed in three main modules. During the query session at the first stage of the evaluation process, the user is asked to provide particular details of the retaining wall system. The parameters asked for are performance, construction aspects and buildability such as the retaining wall system weight, resistance to lateral loads. deterioration of the retaining wall components, installations of all the services' components within the wall, dependence of the wall construction on weather conditions, degree of inspection required and type of complexity of the formwork used. Based on the above factors given by the user, CADDS will seek and match within its Detail Properties Module, a particular wall type that best matches the user requirements.

If the user is satisfied with the solution. further information would be generated by CADDS which outlines the wall system properties such as, the outline geometry of the details, the position. shape, size of each component in the assembly, the attachment type of each component and the cost of each type. The user will further be asked through several questions, to assign numerical values or select multiple attributed criteria presented by the system such as Great Importance, Fair, Moderate, Minor and Not at all.

Once all the required answers have been provided, the system will provide the user with three explanation reports which deal with the detail selection, the buildability assessment, and the implication of the selected detail design.

System limitations

The aim of CADDS is to provide designers with design details from previous design solutions which have little buildability problems. The system has proven the theory which indicates the influences of detailed design on buildability of a project. The system is capable of diagnosing wall systems under certain requirements specified by the user through the structured questions built in the system. The system also relies on the available detail design catalogues stored in the system database to generate the wall type recommendations.

Since CADDS runs as a single expert system which is not built on the product and process model of a project, future integration with other domain models in the project life cycle especially, the architect or structural engineer utilising CAD applications is almost impossible. In addition the system requires great efforts to maintain and update the data base system in order to include new cases of design details.

The CADDS also has various other limitations such as the total cost of the wall system does not represents specific labour, material and equipment type required to be used, as well as what duration is required for construction. The user is only presented with the components cost of the wall system, i.e. concrete, stop bar, kicker, reinforcement, formwork and graphical images for comparison.

4.3.6 MOCA

The research work is currently being conducted in Department of Civil Engineering, Stanford University, USA (Fisher & Aalami, 1994). A prototype system MOCA (Model-Based Constructability Analysis) has been developed based on a product and construction process model to optimise the selection of design and construction methods.

Aims and objectives of the research work

The work aims to demonstrate the feasibility of formalising the construction process models and the practicality of generating realistic project schedules through the interaction with the product models. The focus of the research is to provide a flexible system for users to change their design or the various options of construction methods and to obtain the feedback from the generated construction schedule and cost estimates.

System architecture

The MOCA system is implemented on three types of computer applications, namely, the graphical application, the project management application and the AI programming tool. The knowledge base and the mechanisms of the evaluation is built in the Design ++ which is linked to AutoCAD to visualise the geometry of the product model. The product model is also connected to Primavera to visualise and manipulate the scheduling output. The product model which is represented on Design ++ acts as the system repository to store the project specific data which is later used with the construction model to perform the buildability assessment.

Evaluation methods

The system used the product model and construction process model to obtain the project specific information. The knowledge and data about particular construction methods is formalised by both models. The project specific data is obtained from AutoCAD after the design has been drawn.

The objects of the design model are represented on the product model in Design++. Using the product and construction process models, users are given various options of construction methods to be tested with the design. The essence of the system is the capability of the system to provide a variety of construction methods for the users to explore, in order to get optimum construction methods for the design. The construction method selected would be incorporated in scheduling and cost model which is performed by Primavera System to reflect the duration and cost anticipated by the design and the selected construction methods.

System limitations

Currently the system evaluation is limited by the scope of representation from the product and process models. Some processes for identifying the user interface to create zone or construction areas and the knowledge to create the activities sequence between the zones are being implemented. The system is also limited by the modelling domain in particular the product model to represent lower level of abstraction e.g. component, the structure types and the construction methods.

4.4 Reviews of the buildability assessments application systems

The description from various computer systems for buildability assessments earlier, suggests that designers could not fully evaluate their design solutions unless various aspects of construction which could influence the construction activity are considered such as specification, layout of the structure, dimensional tolerance, physical geometry of the elements, the construction methods, the construction processes and site orientation. It also highlights that the methods of the buildability assessment systems vary, i.e. from using a number of structured questions to obtain general information from a construction plan for the design (PREDICTE, IKBS, CADDS) to direct interpretation of detail design objects from a project model on a graphical interface system (MOCA, COKE).

The factors used for buildability evaluations also vary between the assessment methods. However, the general indicators that are normally used in most of the systems to highlight the effect of buildability on design are the cost and time (PREDICTE, IKBS) generated from construction plan. Using these types of buildability assessment methods, the user could compare the estimated cost and time of their design solution by running the system several times using different designs and construction data.

In some buildability evaluation systems (COKE, MOCA, CADDS, The Dimensional Bay Design System), depending on their aspects of buildability being analysed, instead of providing the cost and time indications, they provide the final version of the design solution with less buildability problems. The processes are executed by altering the attributes of the design, such as structure layout, the elements size and shape or the structure elements orientation, that contribute to buildability problems based on construction aspects such as dimensional tolerance, construction methods. etc.

Besides the above issues, the majority of the buildability evaluation methods described earlier also show that the design evaluation is not performed in an integrated approach where multiple views are required to be considered simultaneously, in order to obtain optimum design solution. For example, changing the layout of the structure element to reduce buildability problems related to a construction method (in this case formwork) might optimise the advantages of buildability on the use of the formwork, but could also create buildability problems on other design aspects such as dimensional tolerance of other element assembly, incompatibility of specification, or the construction process aspects such as transportation. reinforcement work, labour requirement, concreting requirement, etc.

Since, buildability assessment requires various evaluations from different perspectives either in design or construction, and as it demands to be considered collaboratively, the project specific construction information collaboratively gathered from design and specification. construction plan, site layout, estimating, etc. would make the buildability evaluation more acceptable than other approaches. The key concepts to buildability as prepared by CIRIA (1983), CII (1986), and others in Chapter 2, which suggests that designers should produce designs which have higher factors of standardisation, repetitiveness, detailed simplicity, specification development for construction efficiency, modular and pre-assembly approach, could be used to represent this collaborative evaluation approach for the buildability.

In other words, since these buildability improvement aspects are related to ease and efficiency of construction, factors such as, specifications, detail simplicity, orientation of the structure, dimensional tolerances, etc., which are design related, and the process of assembly, type of construction activities, the construction methods, the flow of the selected resources used on site and the flow of the construction sequence, plant, workers, temporary work, etc., which are construction related, could be formalise to represent a collaborative evaluation approach for the buildability. If the evaluated design solution has a small number of standardised elements, infrequent patterns, complicated assembly, impractical specification, inaccessible site, etc., it would be subjected to high risk of buildability problems.

4.5 Summary

This chapter has reviewed a number of studies related to the development of construction planning and buildability applications. The review highlights the ability and approach of some application systems in generating the construction plan and the capability of the applications for supporting the buildability evaluation. The review also highlights other approaches of buildability applications in the construction industry.

The following chapter will review the integration issues between applications in the construction industry. This review will lead to Chapter 7 which outlines the proposed method of buildability evaluation in the research. It will describe the approach of formalising the construction planning information based on these principles for buildability evaluation.

Chapter 5
Approach to integration

5.1 Introduction

Design and construction of facilities essentially involves a large number of information processing activities. The integration of applications from different project participants for evaluating and predicting design performance in terms of time, cost and buildability has become a major consideration of AEC. Since integration of project data also contributes to the effectiveness and efficiency of the overall performance of the project life cycle, this issue has been explored from a number of different viewpoints such as between different designers, designers and suppliers, designers and contractors, contractors and suppliers, etc.

Most of the current integration works have emphasised the complexity of modelling the interactions among the involved project participants. This is due to the requirements of extensive human knowledge to interpret and understand information which involves a different range of people and organisations at various stages of the project life cycle (Howard *et al.,* 1989; Froese, 1993; Aouad *et al.,* 1993; Kartam, 1994; Galle, 1995; Alshawi & Underwood, 1996).

In view of the above problems, this chapter outlines an overview of the current approaches to integration in design and construction, the definitions of integration, the aims of integration, the method for supporting the integration of data and models, and the advantages of integration to construction planning and buildability evaluation.

5.2 Overview of the integration process in the construction industry

The construction industry is known as a highly fragmented industry. The fragmentation of the industry exists both within individual processes of construction as well as across project phases in the project life cycle from briefing, design, construction, facility operation, maintenance and demolition (Howard *et al.,* 1989). Due to this fragmentation, the processes of generating, sharing, maintaining of project data among multiple disciplines, or organisations in industry became a major concern for every project. The essence of these processes will determine whether a project can be effectively designed, built, and maintained.

The interest of construction companies to establish a computer integrated system gradually developed since computer systems become widely used by various project participants. At the earlier stage of integration, the trend to integrate different computer systems was initiated by the need to manipulate and share information between a number of computer systems in a company. As various computer technologies emerged such as data base management systems, computer aided design and knowledge based systems, the development of the integration system also progressed through the combination of these technologies. Examples are integrated DBMS and CAD for generating bill of quantities, integrated DBMS and KBS for equipment selection, integrated KBS and CAD for construction planning, etc. These developments have stressed that the trend of integrating the heterogeneous information can bring about tremendous potential advantages in improving the information sharing and exchange. Currently the integration effort has progressed to the extent that integration is aimed to cover every aspect of information generating and sharing through out the project life cycle.

Froese, (1993); Levitt and Kunz (1985), Savindo (1990), Yamazaki (1993), Iosifidis *et al.*(1995), and Alshawi and Faraj (1995) stated that an integrated computer system that can facilitate data sharing and exchange is essential for an effective construction industry. This facility can influence the efficiency and effectiveness of project development including the construction process. For an example, during the design stage, the data representing inner surface of a wall is important to support the interior designer design task, however for the HVAC engineer the data representing the thermal property of the wall (which is dependent on the material's thermal property used in the wall) is important to his/her design task (Riley & Sabet, 1993). Without a generic and dynamic framework for integration, both designers would not be able to use, share and exchange information.

In addition, Ito (1993), Galle (1995) also described that, an integrated computer system which generates, shares, and maintains the project integrated data among the project participants, is difficult to be modelled and implemented. They stressed that the complexity of integration is due to the complexity of representing various aspects and scope of the integration and that the computer systems used in the project vary between participants.

Despite the complexity to define the scope and approach for integration in the industry, many computer systems in the construction industry have also been successfully integrated. Numerous advantages have been projected from the implementation of integrated project data in a computer based environment especially where construction planning (Cherneff *et al.*, 1991; Hendrickson *et al*, 1987; Fenves, 1989; Howard, 1991; Alshawi & Hassan, 1994; Eastman & Fereshetian, 1994) and buildability evaluations (Gray; 1986; Alshawi & Underwood, 1996; Jergeas, 1989) have to be performed.

5.2.1 Definition of integration

Integration in simple words means combination and cohesion. When applied to a computer system it implies a technique to share a common database which can be accessed, used, and updated by multiple applications or users. The information in such integrated systems is organised in a logical way and demonstrates a centralised behaviour with consistent and non redundant data

(Howard, *et al.* 1989). Since the construction industry is comprised of a variety of professions and organisations, the integration aspects will occur on various dimensions and at different phases e.g. between designers at design stages. between various design teams at the design and construction stage, between design teams and construction teams at both the design and construction stage. etc.

As the industry witnesses more integrated systems, the need for better techniques of integration to support exchange/sharing data or information between professions/individuals, departments, entire organisations will increase. At project levels, the data types which are normally exchanged between project participants, include data representing the physical properties of the design (e.g. such as specifications, geometrical data, engineering data, etc.), instructions. resources, cost and construction activities. As the scope of integration becomes wider in order to allow greater sharing/exchanging of information, the objectives of integration would also change in dimensions, from data to models, knowledge. goals and lastly, all project information to accommodate the entire industry (Betts *et al.* 1993). This ideal concept of integration which is currently being pursued to support the entire construction industry is called Computer Integrated Construction (CIC). Miyetake and Kangari, (1993) define CIC as

> "a strategy for linking existing and emerging technology and people in order to optimise marketing, sales, accounting, planning, management,

engineering, design, procurement, and contracting, construction, operation and maintenance, and support functions".

Besides aiming to have sharable and readable information between the parties, the questions of what, who, when, why integration is required on the various aspects, levels and dimensions of the integration, still remain to be clarified. While the CIC is targeting wider and higher objectives of integration, Miyatake *et al.*,(1993) stressed that currently there is no standard approach for CIC, because the strategies for applying the concept is still being investigated.

5.2.2 Aims of the integration

The main aim for achieving integration between project participants is to facilitate a meaningful data exchange at real time as and when required throughout the project life cycle (Howard, *et al.*, 1989; Yamazaki, 1993; Ford *et al.*, 1994; Kartam, 1994). Various researchers agreed that the data in an integrated system must be able to be viewed from different perspectives and levels of abstraction besides it also depends on the requirements of the particular user.

The integration approach should also aim to facilitate the use and reuse of project information. The fact that design and construction information have different views and levels of abstraction, complicates the integration process. To facilitate the use and reuse of a large magnitude of information, the concept of dynamic data models which can be easily adjusted to meet the specific requirements of the end user and the computer technology has to be addressed (Eastman, 1993; Bjork 1992; Aouad *et al.*, 1993; Iosifidis *et al.,* 1995; Alshawi & Faraj, 1995). This would allow the data models to be inquired, extracted and modified as the state of the model changes.

5.2.3 Approaches to data exchange

Integration in a computer can be applied in three ways, namely through third party files, a standard data exchange and a conceptual model. Each of the integration techniques although applicable, imposes its own limitations. In a third party, data is stored and retrieved in a predefined file structure such as those used by a particular database management system (DBMS). Since each data file has to be predefined to cater for the need to store and retrieve data, any changes made to the data structure could impair the context of the data for other users. Due to this limitation and since design and construction data are dynamic in nature, the data file technique would not be able to cope with the demand for a flexible data structure, in an integrated approach (Munns *et al.*, 1994).

Since design information is normally exchanged between various parties involved in a project, a means of standard communication was introduced to support exchanging and sharing of the design information. A standard data exchange format emerged which provides communication needs between various CAD systems. The 'industry standard' format of DXF and IGES was accepted as a de facto for exchanging geometric information.

This standard of data exchange format has facilitated the integration of information between different CAD systems, without human interpretation and data reformatting. For contractors, the standard data exchanged format has simplified the use of the design information obtained from the designer in CAD for construction simulations. However, this format was soon found to be inadequate to represent the project information since geometrical data alone such as line, circle, co-ordination etc. can not provide meaningful data in the form of an object which is important for other applications such as construction (Ewen & Alshawi, 1993; Kartam, 1994; Tah *et al*, 1994).

5.2.4 Using product modelling for data exchange

Since graphical data exchanged through DXF or IGES alone is in insufficient to support complete representation of project information across its life cycle, data exchange has moved to conceptual *product modelling*. The use of *product modelling* is seen as an enabling factor that could provide richer representation of product data such as geometry, topology, relationship, tolerance, design attributes and features, to be completely defined as a component part or an assembly of parts for the purpose of design, analysis, construction, etc. (Eastman, 1993; Bjork, 1992; Froese, 1995; Aouad *et al.*, 1993; Alshawi,1995 ; Tom, 1995). However, based on many ongoing research, the *product modelling* approach is only effective, if object definition and relationships are unambiguously defined and standardised. These aspects of data exchange have set a new direction for researchers to provide *product data models* which can be utilised by various project participants through out the project life cycle.

This finding to standardise the product and process models has also become the fundamental aim of various international efforts. Since PDES (Product Data Exchange Specification) and STEP (STandard for Exchange of Product Data) which represent the international interest, have initiated the development of standard product modelling for data exchange. Their main objective is to create a standard data model that enables the capture of information comprising a computerised *product model* in a neutral form without loss of completeness and integrity throughout the life cycle of product (Watson, 1993; Wix, 1989: Poyet, 1994).

The development of a computer based information system to support design and construction integration, requires the provision of a facility for exchanging information of the project throughout its life cycle (Eastman, 1993). *Project model* which consists of a product and process models of the project in its life cycle, is seen as a popular approach to provide the facility for exchanging/sharing information or data, among the project participants in the integrated environments. This is due to the model's capabilities to highlight all aspects of its information and relationship requirements over the various stage of the project life cycle.

Various factors have to be established in developing *the standard product model* such as the substantial amount and different types of information generated within a project, the variety of project type, the considerable number of different experts involved, the vast number of building materials and specifications, the complicated links and processes involved in the project, variations of national and regional standards, diversity of clients, etc. Since these factors complicate the standardisation effort for integration, the *unified standard product models* representing construction processes using information protocol led by STEP are still under development (Thorpe *et al.*, 1994).

Definition of product and process model

Wix (1989) defined *product model* as representation of a real structure or object, in a manner which allows it's characteristics to be observed without having to build it. Van Nederveen (1993) described *product model* as an information model of a product, in which product data is stored in an integrated way, including information on the product parts. their properties, relations and behaviour, during different product life cycle stages. Faraj (1994) defined *product model* as a software representation of engineering data that supports a product throughout its life cycle from specification to the disposal of the product.

On the other hand, Froese (1995) defines the *process model* as the procedural contexts in which products are developed either at design, construction, etc., stages. The *process model* represents the whole aspect construction process from briefing to demolition. For example, a *process model* of a construction process is composed of categories of the activities carried out by the project participants and the relationship among the activities in the categories. The *process models* highlight the information (process data) describing production activities (design, planning, construction), the processes structure, the operations and paths. In addition Froese (1995) and Alshawi & Underwood (1996) also added that the combination of both product and process models would represent the whole *project model*.

Product data is data that describes the function and physical characteristics of each unit of a product from its requirements at inception to its configuration at time of retirements (Watson, 1993). The *product data* of a product can include anything about the product, from selling price to the way in which it was manufactured, assembled, inspected, maintained and disposed.

For the purpose of enhanced communication, *product data* needs to be either exchanged between parties or integrated in share data models. Due to this factor, standardisation of data definitions in the product, and process model, is essential to avoid mismatch of information. Watson (1993) noted that standardisation of engineering information, relating to a *type* of product which facilitates the unambiguous transfer of information between applications software depends on the product modelling approach.

Since, the purposes of the product modelling include the representation of the product model throughout its life cycle, an agreed form of information model which defines how information relating to a *particular* product should be coherently structured between applications such as design, constructions, cost, planning, maintaining, etc.

5.3 Integration through product models

If a standard product data model for individual domains are developed, then an approach is required to integrate them to form a product model. Hannus *et al.* (1994, 1995) outlined several approaches of integration for product data models which could be applied to the construction process. These are:-

- inter-application mapping: specific mapping rules are applied by the system which needs to be integrated where entities of the sending system are translated to the entities of the receiving system i.e. one to one integration.

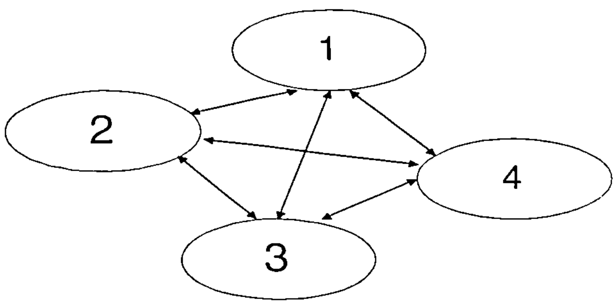


Figure 5.1 Inter-application data sharing

- neutral model: utilising a common neutral model (tool-independent) where each application provides an interface which translates the application specific entities to the entities of the neutral model and vice versa.

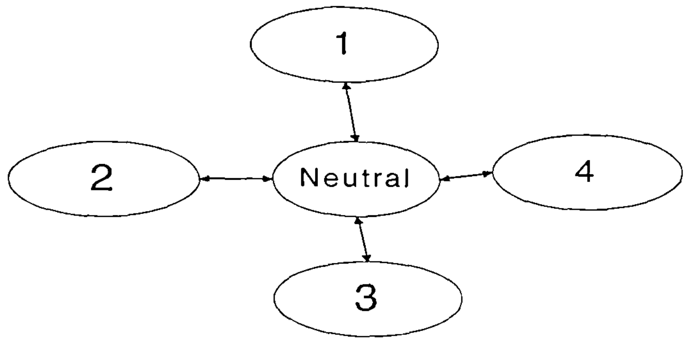


Figure 5.2 Sharing data via neutral model

- application domain models: this is the basic idea of the " application protocol" approach which currently dominates the development of ISO/STEP standards. Assuming that specific application domains exist and have a definable scope, standardisation may address application domains which do not necessarily share common definitions.

- common resources: different application domains are supposed to share common resources i.e. the basic data types which are used to compose application specific entities. This approach allows at least sharing of low level representation between distinct applications.

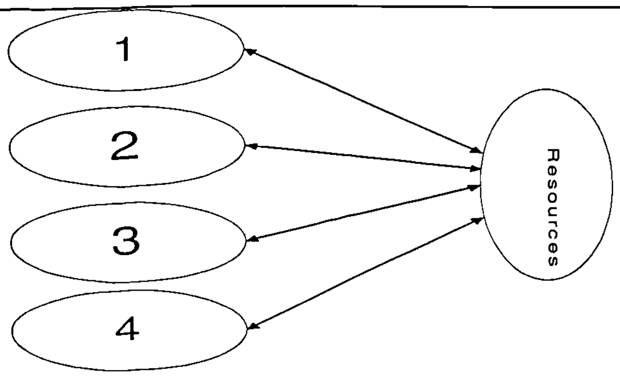


Figure 5.3 Sharing data via common resources

- common core model: common objects used by different perspectives are identified as central objects to be shared across the project life cycle e.g. building elements, space, system, etc. Although, the approach is feasible for construction, however, any application specific data outside of the core would be lost in data exchange.

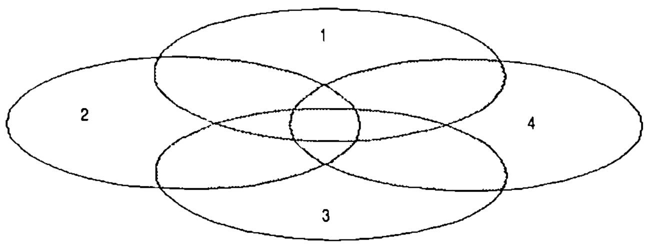


Figure 5.4 Data sharing via central core

- mutually exclusive common models: two applications sharing data that is not applicable for any other applications.

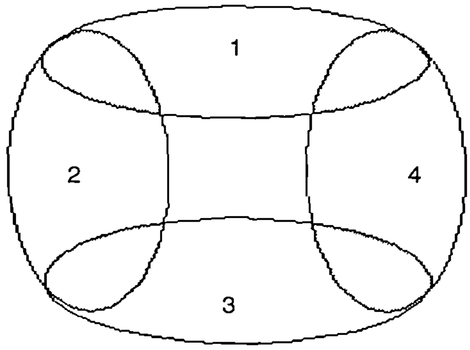


Figure 5.5 Data sharing via a mutually exclusive partly common model

Each of the integration approaches described above however, has its own advantages and limitations. Although some of the approaches are capable of satisfying a particular level of the integration needs, since the scope of integration in the construction process is enormous, none of the approaches have been fully implemented and therefore can not prove to satisfy all aspects of integration requirements over the project life cycle.

5.4 Integrated models

Many product and process models, have been developed in the industry to represent the various aspects of the construction process since STEP and PDES initiated the product modelling approach for integration. The models which have been investigated range from the meta model, conceptual model, reference model, to a specific model (Hannus & Pietilainen, 1995). Some of the developed models have been defined to represent the high level models of the construction process such as STEP BCCM (Building Construction Core Model) (ISO 1994) and

IRMA (Information Reference Model for AEC) while others represent the actual product, and process models of the construction process (Froese, 1995). For STEP BCCM and IRMA models, they are intended to serve as unifying reference models for more detailed models, for standardising information exchange (Froese, 1995). Augenbroe (1995) described the primary objectives of the core model developed in STEP BCCM and IRMA are :

- to provide a conceptual model of the common information requirements amongst disciplines within the Building Construction industry which could facilitate a means for sharing and/or exchange of information to a degree commensurate with need.

- to provide a set of consistent model constructs for areas of information use which can be used and specialised by more specific discipline models so as to ease and improve the integration of the discipline.

For example, four general major types of building construction object are identified in the STEP BCCM such as :-

- *product objects* which are system and components of the constructed facility itself.
- *process objects* representing the processes or actual construction effort on the project.

- *resources objects* representing the resources used on projects such as materials and equipment.
- *control objects* are items which control, influence or constrain other project objects such as contracts, budgets, design standards, etc.

Based on the generic models described above, other detailed construction process, and product data models, would have to be developed to capture the various aspects of the project life cycle such as briefing, preliminary design, detail design, structure analysis, heat and ventilation analysis, services analysis, estimating, construction planning, site layout, material management, plant selection, building maintenance, etc. A number of research projects have been carried out to model and integrate several construction disciplines. Such projects are the ICON (Intelligent Integration of Information for Construction) (Aouad *et al.,*1993), COMBINE (Computer Models for Building Industry in Europe) (Augenbroe, 1994), IBPM (Integrated Building Process Model) (Sanvindo *et al.,* 1992), etc. However, since the life cycle of a project is dynamic, complex and enormous, and since the research organisations used a different paradigm of integration, most of the types and scope of product, and process models, developed by these organisations represent various partial areas of the whole construction process.

The ICON research work followed a top-down approach which aims at producing integrated product, and process models, for the various 'perspectives' of the stages involved in the life cycle of a project. High level objects have been defined to reflect the main stages of a construction project such as *Defining, Procuring, Designing, Constructing, Commissioning and Maintaining.* Each of these high level objects are further decomposed to reflect the product data model thus representing detailed levels and the concerned processes such as construction planning, estimating, etc. (Aouad *et al.*, 1994).

In COMBINE, the type and the scope of product models represented is mainly concerned with the design stage for energy and HVAC (Heating Ventilation Air Conditioning). Since COMBINE aims to produce an intelligent integrated building design system (IIBDS), the result of their product, and process models, are only limited to the design stage. A conceptual integrated building model (IDM) that combines six actors was produced which acted as a central common data repository for exchanging data (Augenbroe, 1994).

The IBPM (Sanvido, 1990) research work, on the other hand aimed to produce an integrated building process model as a foundation for information architecture in AEC. Like the ICON project, the developed process model was defined in a top-down approach manner where five major process were identified, namely *manage facility, plan facility, design facility, construct facility* and *operate facility.* The product model, and process models, representing the facility is divided into several levels which represent different degrees of detail for the facility objects (Savindo *et al.,* 1992).

5.5 The key features for the integrated product data model

Several researchers (Bjork, 1992; Eastman, 1993; Ahmed *et al.*, 1991; Rosenman, 1993; Alshawi, 1995) have suggested several key features for the product model to support the integration needs over the project life cycle.

Bjork (1992) suggested that the product data model should represent:

- all stages of the project process from briefing to maintenance
- covering all the different participants
- be comprehensive
- be independent from software and hardware systems
- contain non redundant information and
- the output documents format and content should be independent from the structure of the model.

Eastman (1993) argued that a product data model in construction has two roles; supporting decision making regarding the alternative plans and designs, and supporting the monitoring and managing functions of an existing facility. During the design stage he proposed that the product data model should be able to provide vertical integration between designers and horizontal integration to support different uses and goals of the product model over various stages of the project life cycle. It should support;

- *version control*: track of changes are facilitated to guarantee use of a consistent set of data. It also allows the representation and management of alternative designs, incorporating various assumptions.
- *integrity management*: the product models carry within their data a number of relationships that a complete model must satisfy. The relationship extends from the data, semantic relationship with other domains, etc.
- *concurrency:* as the product model is used to support a variety of users, during some stage of the product model, parallel and multiple modifications of the model could be needed, therefore concurrency control methods are required to maintain model consistency.
- *extensibility:* Issues of the model extensibility must be addressed in its dynamic stage, as decisions are made on the product.

Rosenman (1993) stressed that the development of the standard models for the product model is affected by how well the static and dynamic attributes of the design models are defined while accommodating other different views. This is an important issue because design models are normally produced incrementally over a period of time. The dynamic characteristic of the product model should extend towards construction, occupation, maintenance and demolition.

Hannus *et al.,* (1994) also proposed that to provide a product data model for every aspect of the project life cycle, issues related to the development, dissemination and maintenance of the model, in relation to aspects such as a common core model, common meta model, flexibility, extendibility, modularity, have to be fully understood. In addition, the need for the model to facilitate the identification, specialisation, generalisation, mapping, simplicity, support reuse of knowledge, decomposition and independence of implementation, also partly effects the proposed product data model.

Besides the problems relating to the development of product and process models, Alshawi (1995) proposed that the product, and process models, must be able to support the general framework for an object life cycle in the models, from its creation to deletion. The ability of the framework to recognise the state of the object (creation, supplement, use, etc.) when it is implemented in the system, will enable efficient management of information within the integrated environment.

Although various requirements have been outlined for the product model to support the life cycle of the project, the above key features address different issues and reflect the difficulty in achieving a single product model. Few researchers (Van Leeuwen *et al.,* 1995; Ramscar, 1994) suggested that representation of the various stages of the project life cycle, using a product data model approach could not be achieved to provide total integration or exchanged standard at the detail level, except for high level of abstractions.

5.6 Reviews of current product and process models supporting construction planning and buildability evaluation.

Most of the current developments of product, and process models are centred around establishing a standard product and process model. The aim is to allow greater effectiveness and efficiency in sharing and changing information between various participants in the project life cycle. The extent to which the product and process models are developed fall into two categories. top-down or bottom up. The top-down approach starts from the strategic level to operational level, such as applied by ICON (Aouad. *et al.*, 1994) and IBPM (Sanvido. 1990) project, while bottom-up is the opposite approach such as used by the COMBINE (Scherer, 1994) and the SPACE (Alshawi & Faraj, 1995) project. Each of the above product, and process models, also present a limited scope of integration in construction process.

Nevertheless, the scope of data represented by a product model highly depends on the uses and goals of the building model (Eastman, 1993). At the design stage, the requirement for data from the product model is oriented towards solving design problems while at the construction stage the requirement for data from the product model is for realising the conceptual design model into a physical model.

Since, the requirement of a product model for construction planning starts when a design model is completed, in order to support construction planning, and the buildability evaluation, ideally a complete representation of project data models will be required. The product data models should represent full descriptions of the product model, while the process model should represent the functions involved in the domains. The product model should contain all the necessary information required to realise the project such as for assembly, scheduling, taking off quantities, etc.

The reviews which were carried out on the application systems in construction planning and the buildability evaluation (in Chapter 4), indicate that the majority were concerned with showing the impact of the developed systems on the construction process. For example the knowledge and the decision criteria for activity sequencing (Echeverry *et al.*, 1991; Kahkonen. 1993), the relationship between design objects, action objects and resources objects, when developing a construction plan (OARPLAN; Darwiche *et al.*, 1989), the importance of integration between estimating and construction planning (Yau *et al.*, 1991), the power of object oriented applied in the construction planning domain (Yamazaki, 1991), the decision criteria when criticising construction plans (GHOST, Navinchandra *et al.,* 1988), etc. For buildability evaluation, the use of the product model was only applied in COKE (Fisher, 1991 & 1993) and MOCA (Fisher & Aalami, 1996) systems. The product model was integrated with the construction methods model to provide the buildability evaluation. Although, both systems utilise the product model in their buildability evaluation process, the conceptual model of buildability evaluation proposed, was not presented.

Nevertheless, since the integration concept through product and process models were recently recognised, the importance of a well defined product, and process model, for integration application, gradually became a major consideration for system development. Therefore, the majority of current research work concentrates on producing a reliable and accurate product and process model, representing various views and stages of the project life cycle. Besides, accuracy and reliability are the major issues of the product and process, currently, no one has come out with methods of measuring the quality, accuracy, integrity and reliability of the proposed models in the construction process (Vincent, 1993).

5.7 The advantages of system integration to construction planning and buildability evaluations.

The implementation of the integration concept can bring about numerous advantages to construction planning and buildability evaluation. The degree of benefits depends on three issues; the technological aspects of the software, the scope and approach of integration. The technological aspects of the software refer to the type of software used e.g. databases, rules base, knowledge base, graphical interface system, project management application system, etc. The scope of integration describes the extent of integration on the various domains in the construction industry, while the approach of integration refers to the method used to achieve the integration.

Among the advantages of integration for construction planning and buildability evaluation, is that integration can eliminate most of the tedious operations involved in capturing project data. It has also reduced unnecessary duplication of work for data input (Howard, 1991; Levitt *et al.,* 1988). Information can be exchanged accurately and reliably throughout the system (Howard. 1991).

The current project management software is a knowledge poor analysis tool, and only capable of manipulating construction data which is normally provided by the user. Through integration with KBS, the limitation of the existing project management system can be improved. Various types of complicated decision making processes can be assisted at relatively short times (Levitt & Kunz. 1987; Mohan, 1990). For example, the KBS can be used to assist in identifying building elements and its construction activities (Cherneff *et al.*, 1991; Hendrickson *et al.*, 1987), selecting and allocating resources (Shaked & Warszawaki, 1995), sequencing construction activities (Kahkonen, 1993), calculating activities duration and cost, etc.

Using graphical interface such as CAD or a virtual reality package, construction data can be represented in 3D to simulate the construction process which can quickly assist users to evaluate the construction plan and the buildability of the project (Alshawi & Hassan, 1997; Euler, 1993). Furthermore, when product and process models, are used in the integrated system, wider and various levels of integration can be achieved (Levitt *et al.*, 1988; Aouad *et al.*. 1994). For example, other stages of the project life cycle can easily be added in to the system such as estimating (Yau, 1992; Alshawi & Underwood, 1996), site layout planning (Alshawi & Sulaiman, 1996), buildability evaluation (Fisher, 1991; Fisher & Aalami, 1994) materials management, etc.

5.8 Summary

This chapter has provided an overview of the integration process, its approaches and the advantages of computer integration in the construction industry, particularly regarding the integration of design, construction planning process and buildability. The following chapter will describe the proposed buildability assessment which utilises construction planning information and buildability improvement principles.

Chapter 6
The Proposed Buildability Assessment

6.1 Introduction

As described earlier in Chapter 2, the major factor that hinders the designer in evaluating buildability is the absence of the project specific construction information due to the separation of design and its construction stage. From the discussion in Chapter 4, various researchers have formulated different aspects of buildability evaluation systems using knowledge based systems that could assist designers to reflect on their design. Some of the evaluation systems utilised real time project specific information from integration with a graphical interface package while others derived project information through a general series of structured questions built within the knowledge based system.

Based on the scope and the aims of the buildability assessment, different types of evaluation results can be presented to designers ranging from a general indication of time, cost and resources, to specific design solutions of a structural layout, construction methods and design detailing. The variety of buildability evaluations developed so far for design, highlights the fact that the problems are enormous and complex and covers various aspects of design and construction.

In this chapter a quantitative approach for buildability evaluation is proposed. The proposed approach collates, analyses and uses various information; i.e. regarding the design components, specifications, construction planning, estimating, etc. If implemented in an integrated object oriented knowledge based system, an interactive and iterative evaluation can be performed with relative ease.

This chapter outlines the proposed approach which includes the formalisation of specific design and construction information, the use of several buildability aspects to assess the impact of design on construction, and the general framework for the evaluation process.

6.2 Key requirements for a quantitative evaluation approach for buildability

Buildability evaluation should be part of the performance evaluation of any design solution. Therefore, it is essential to establish an evaluation approach that could perform this requirement based on construction information at the design stage. It should also be of a quantitative nature to enable designers to analyse the buildability of their design, based on the planned construction process. Examples of construction data which necessary for this purpose are the assembly and the construction process, the construction sequence, the resources type and flow, the construction methods, the site constraints, the continuity of the construction processes, conversion factors of basic materials to form the element or components, orientation of site, selection of plant and temporary works, etc.

As is normal practice, most of the project construction information can only be obtained at the construction stage. However, before a project can be realised, the constructors usually manifest their construction approaches through the construction planning process. Therefore, the construction information generated by this process, if properly structured, can be utilised to evaluate buildability of a design. It is therefore important to formalise the construction planning process in order to make the best of the construction information.

Designers would then be able to diagnose their design against buildability from the construction perspectives. However, the construction information alone will not be significant to show the effects of the design solution against buildability aspects, unless the basic factors that contribute to the buildability aspects are recognised and structured with the construction information to reflect the buildability impact.

Since the key aspects of buildability are qualitative concept rather than quantitative, a weighting and scoring system will be required to be developed on those aspects based on the construction information. This approach should indicate the scale of "buildability" for the various building elements. A graphical representation of buildability scores must also be adopted to simplify the interpretation of the large amount of information. A comparative analysis on such a presentation would highlight the buildability effect on each of the design elements.

Finally the evaluation must be performed in an integrated environment where the information can be effectively used to check the design against buildability concepts (as described in Chapter 2) such as simplification, repetitiveness, standardisation, building tolerances, communication, etc.

6.3 Information required for the construction planning

The type and scope of construction information which is necessary to support the buildability evaluation vary according to the methods applied for the evaluations. In general, information about design and other construction disciplines such as estimating, site layout planning, plant, materials, etc. are required.

6.3.1 Design information

The design information normally represents the physical properties of the facility such as the element type, specification, component, dimensional, location and co-ordination, and a topological relationship.

Element type

The physical elements of the building/facility act together to provide the enclosed space for the services required. They can be aggregated to several distinct classes such as structural elements, services elements, architectural elements, etc. The physical elements of a building do not presuppose anything about the construction approach to be chosen or the resources to be used. Each element can have different specifications and attributes, as well as having different functional and performance requirements, moreover each element would have different constructional aspects.

Construction planners have to extract the necessary data from the design solution in order to establish their required construction activities and resources. For example the T shape reinforced concrete column and the square shape brick column or S brick wall and reinforced concrete wall; all would need different construction activities and resources to be realised.

Elemental specification

In order to construct a design element, its main properties and its components must be identified. This includes:-

a) the composition of the elements.

This covers the material components, material composition, material type, etc. like Engineering Brick, Reinforced Concrete 1:2:4. etc. Availability of detail specifications for the element's components will determine the construction activities and the processes required. Since each element and its components might use different construction activities, resources and construction methods, the complexity of realising these elements can be therefore estimated.

b) the geometrical property of the element

This includes the length, width, breadth, location, shape. size, weight, etc. Each of these properties can have various effects on the construction activities, resources, duration, cost, etc. They determine how an element can be constructed, the duration that would be required to construct it and its relevant construction methods. For example a circular column needs a round formwork compares to a square column which requires a square formwork.

If the rounded column height is higher than others, extra formwork, labour, duration, and a temporary facility will be required. Based on the location of the element, construction planners can also determine whether a special requirement is needed to realise the element, i.e. concreting a column on the tenth floor of a building requires special equipment to transport the concrete.

c) the quantity of the element and its materials

This information is required to determine the duration of the construction activities, the right number of resources and the method of construction.

Element topological relationship

The relationship between the elements is described as a topological relationship. The topological relationships (Echeverry *et al*, 1991) required are:

a) Supported_By ; this type of element relationship shows that one of the elements is physically supported by the other element. It normally represents a structural element relationship, i.e. between column and beam or column and slab, etc. The relationship implies that any activity that acts upon a supported element has to follow the activity that installs the supporting elements.

b) Attached_To; this type of relationship shows that a non-structural element is physically attached to a structural element, e.g. suspended ceiling attached to a slab, or a partition attached to two columns.

c) Embedded_In; this type of relationship illustrates that an element is located inside another element for a specific purpose, e.g. wiring components embedded in the wall or floor, a footing embedded in the ground.

d) Covered_By; this relationship describes that an element is protected by another element with lesser purpose than the embedded_in relationship, e.g. a wall is covered by a plaster finish or paint, or a floor is covered by a floor tile.

6.3.2 Information required from other disciplines

The physical information of the design alone would not be sufficient to develop a construction plan. Information which is provided by others such as those from the estimators, plant managers and site managers are required. This information includes the selected construction methods, the production records of the construction resources, the site constraints imposed to the selected methods, and the basic cost of the selected resources.

Selected construction methods

The selection of a construction method for a construction activity required collaborative efforts from the construction management team. Not every plant or temporary facility available could be used on a particular project. The selection factors such as operability, maintainability, suitability, and production output of the plant or temporary facilities based on site constraints are normally considered when the selection has been made. When the selected construction methods are applied to the construction activities the duration can be obtained. From the construction plan, the utilisation profile of the construction methods will be used to evaluate design for buildability.

Resource production records

The selected construction methods for all the construction activities define the resources which are required to construct the project. The production outputs of the resources, determine the duration of the related construction activities. The cost of the resources over a period of construction is used to obtain the estimated cost of the construction activities.

6.4 Construction planning information for evaluating the design buildability

The purposes of buildability evaluations are to help designers to examine the impact of their design on construction, while maintaining the functional and physical requirements of the design. Information required for this purpose is the main output of the construction plan, such as construction activities, the construction process, construction methods, construction resources, construction time, and construction cost.

Construction activities

A construction activity is a representation of compounded construction processes, or tasks required to build a particular design facility. Specific rules are used by construction planners for generating construction activities and establishing their type, aggregation level, and attributes. These specific rules are relatively influenced by the properties and the specifications of the design itself. As a normal practice, the construction planners normally have to identify such information such as the type of design element e.g. beam, slab, wall; its material composition e.g. reinforced concrete, composite steel and concrete, etc.; and its components e.g. concrete and reinforcement, brick, mortar, etc.

For example, if the element type identified is a beam, of a reinforced concrete type which is made of concrete and reinforcement bars, the beam would have an elemental construction activity say "Construct Beam". When this activity is decomposed, more detailed tasks can be defined such as "Moulding", "Install Reinforcement" and "Concreting". At this point, the activity "Construct Beam" only needs three major tasks to construct itself. However, other attributes of the design element might require additional or specific extra tasks. For example, if the beam is located at ground level, extra activity would be required i.e. "Excavate Ground Beam" and if it is located on the first floor level, an extra activity such as "Install Falsework and Formwork" would be needed.

This construction information can therefore be used to evaluate design attributes based on the type and the required construction activities. The information is particularly important when the designer applies different shapes, specification, location and etc. Since each activity indicates the nature and type of the work required to realise the design element, this construction information is essential for the buildability evaluation.

Construction process

Construction process is defined as the approach used by the contractor to realise the design element using the basic construction activity. The construction process is affected by various factors namely, the construction technology and specifications of the design, the construction methods, the availability of space, safety regulations, code of practices, etc. The construction is also affected by the detail process of how the construction is performed and how the arrangement of the tasks is carried out. Usually the construction process is complex and encompasses several distinct processes, each having its own technology and work task sequences. The formulated construction processes are unique for every single project since each project has a unique design specification, site location, functional and performance requirements. To some extent the arrangement of the construction process has to be specifically formulated in various sequential procedures (i.e. overlapping or concurrently) to cope with the design specification and attributes.

Variation in the construction process occurs when different skill trades are required. This is mainly caused by changing the materials of the design elements. The produced design solution dictates where the construction materials will be located and therefore stating where the trade skills and plant are needed.

For example, a reinforced concrete column would require construction tasks such as fabricating reinforcement, lifting reinforcement, installed reinforcement, installed formwork, and concreting, while a composite concrete steel column would require construction tasks such as "Place steel column", "Bolt steel column to the base and other elements", "Install formwork" and "Concreting". Since the two columns have different specifications, their expected construction process will also differ. Based on these facts, designers can examine the buildability impact of their design with the required construction processes.

Construction methods

The construction method represents the technique and the resources used to perform the construction tasks. There are various options of construction methods in which a construction of a design element can be carried out, such as, method of lifting the resources, batting and mixing of the construction materials, transporting, excavating, fabricating, providing temporary facilities, etc. Although each method has a different impact on the buildability of the design, their selection is highly dependent on the specification of design elements, site factor, the speed of construction required, contractor preferences, and the cost of using the method.

For example, to build a concrete floor on the 1st floor level, the construction tasks involved would be the erection of formwork and falsework, installation of reinforcement, and concreting. Each of the construction tasks requires different resources and techniques, which can also be done using different construction methods. For example, reinforcement can either be fabricated at the ground, or at the point of installation. Options are also available for concreting which could use ready mix concrete or mix at site. Each of the methods selected would have different approaches for construction, cost and speed of production or erection (productivity). Each of them may also require special plant to assist the construction works. Although, various options are available, contractors normally utilise a single method of construction for a particular type of construction work throughout the project duration unless changing the method is essential to improve the construction process.

To get an optimum buildability from utilising the construction methods, the selected methods should be used constantly throughout the construction period. However, the design specifications and site factors dictate the suitability of the construction methods used for the construction activities. Therefore, designers could repeatedly try other design solutions to obtain the optimum solution in terms of time and cost.

Construction resources

The construction resources can be categorised as labour, plant, temporary facility, and materials. The use of the right resources can effect the speed, efficiency and effectiveness of the construction work. The decision for allocating the quantity of resources for a design element is primarily subjected to their capability and availability. By examining the type and quantity of the resources used, the designer would be able to reflect the effect of their design solution on resource utilisation.

For example, if columns have different shapes and specifications, then different resources would be required to construct the columns. To some extent the column might require different formwork, skilled labour and a construction process. If large numbers of different resources are used to realise a design solution, or the utilisation of the available resources is limited to only a few specific construction tasks, having considered the related factors such as the construction process, site space and safety. the designers would be able to identify whether their design solutions are easily and economically buildable, based on the utilisation of the resources.

Construction time

The construction time for an activity is derived from the productivity output of the resources allocated to realise the design elements. The required construction time varies accordingly to the quantity of the work, production time, the selected construction method, the quantity of resources, the physical environment of the site, etc. However as a common practice, an implicit range of time within which the "normal" duration is tolerated, is used for each type of construction activity. By exercising and evaluating different design solutions using a constant type of construction method as well as the number and type of resources in the construction planning process, designers would be able to determine whether their design is taking a longer time to build, and would also be able to detect the factor that contributes to the required duration.

Construction cost

Construction cost is implied by the various factors from the construction process. As a general practice for design evaluation, the construction cost is used as an indicator to reveal the implication of realising the design solutions on a particular site. For construction planning the basic cost of employing the resources will be used to determine construction cost. For buildability evaluation the construction cost is only a representation of the production cost required to realise the design solution. The construction cost would vary depending on the duration of the activity, the selected construction method, the number and type of resources, and the construction process.

Since each design element has its own construction cost, therefore by comparing and analysing each of the factors that contributed to the construction cost, designers would be able to evaluate their design solution against the key concepts of buildability.

6.5 The elements of the proposed buildability evaluation approach

The proposed buildability evaluation is based on the key principles of buildability as outlined by various researchers (in Chapter 2), and the construction data formulated from the project specific construction plan. A weighting and scoring system has been developed for these buildability principles. These weightings depend on project conditions and only applied for seven intangible factors which influence the buildability principles i.e. element shape, element functionality, onsite/offsite method, dry/wet process, locational factors, element dependency and usability of formwork/falsework. The weightings are given a scale of 0-1 when 0 having the lowest effect on buildability. The values are determined by user/evaluators based on their previous site experience. This study has not addressed this issue and has suggested further studies to be taken in the area in order to develop a clear and more objective methodology to determine these weightings.

The allocation of the general weighting scale in the equation is based on this weighting assumptions. Higher weighting scales would indicate extreme difficulty or constraint. For example, the building element shape varies from square, rectangular, round, etc. Experiences in construction indicate that rounded columns or a complicated shape element is more difficult to build compared to the square column. Therefore the weighting given to a rounded column should be higher than a square column. By having the weighting and scores in the evaluation, the buildability result is determined by the buildability scores and index attributed to the building element. The buildability scores are derived from the buildability elements described below. The buildability index is obtained by summing up all the buildability scores of the building element. The buildability score indicates ease of construction. A higher score derived from the equation reflects difficult construction while a lower score indicates a simpler construction.

This section lists the main buildability elements and its equation which is considered for the proposed buildability evaluation.

6.5.1 Repetitiveness

This is the main principle of buildability which is agreed by various researchers. It is one of the seven keys concepts which is highly recommended for achieving good buildability design (CIRIA, 1983; CII, 1986; Hon, *et al.*, 1989, Ferguson, 1989). In order to obtain clear information on the impact of repetitiveness on the project, a further breakdown of this factor with respect to the property of the building element is essential i.e. element specification, dimensions and material used.

Since each of these properties of the design elements can appear uniquely on the various elements, the evaluation of such properties on construction may be significant.

a) Specification

Different specifications for building elements can reduce the speed of construction, as work adjustment will be necessary as the work progresses. Specific measures would be required on some of the element specifications. The buildability scores calculated are determined by calculating the number of building elements that use a particular type of specification and divide by the total number specifications that fall on the group of the element. A lower percentage represents how a small use of the specification in the building elements increases factors for buildability.

$$\text{Buildability Score} = 100 * n/\Sigma n$$

where n = number of elements which share similar specifications

Σn = total number of the specifications used by an element group

b) **Dimension**

Like specification, dissimilar building element's dimensions or sizes in a project, is likely to delay the construction activities and increases the cost of resources. Element dimensions can effect the decision on resource allocation since it can directly influence the amount of workload to construct the element. The buildability score on dimension is calculated as a percentage from the number of a specific dimension of the represent the element group, over the whole population of the element class. Lower buildability scores indicate lower factor of buildability as the dimension for the element is repeatedly used in other similar building elements.

$$\text{Buildability Score} = 100 - (100 * n/\Sigma n)$$

where n = number of element which share similar dimension

Σn = total number of the elements in the class

c) **Material used**

By referring to the specification, the exact materials type and attributes are identified. Similar to dimension, the repetition in using materials can effect the allocation or resources on the project as well as the construction activities. The buildability score is determined by calculating as a percentage on the number of a specific material being used for the element group, over the whole population of the element class. Lower scores indicate good buildability as the material used for the element is repeatedly used in other similar building elements.

$$\text{Buildability Score} = 100 - (100 * n/\Sigma n)$$

where n = number of element which share similar material

Σn = total number of the elements in the class

d) **Shape**

The shape of the element also contributes to buildability. For a reinforced concrete element, complex shape requires complex formwork thus consuming more time and cost for construction. T shape or L shape, Rounded shape is more complicated to be built compared to just a square or rectangular or a simple shape. Since the shape of an element could not be directly quantified to illustrate its construction difficulty, a general weighting scale illustrating its difficulty is applied in the calculation of its buildability score.

For simple square shapes the weighting scale assigned to the element should be higher compared to the complicated shape of an element, either column, beam, slab etc. A default weighting scale is already allocated for each shape which can be changed by user/evaluator. The calculation of the buildability score is determined by the equation below. Lower scores indicate good buildability as the shape applied to the element is repeatedly used in other similar elements.

$$\text{Buildability Score} = 100 - (100 * W)$$

W = weighting scale between 0 - 1

6.5.2 Functional requirement

The functional requirement of a building element indicates whether the element required is part of a structural, aesthetic or services system. The functional identification is normally used to produce a logical sequence of construction. Since structural elements support other building elements, the element is normally given high priority during construction. This functional indication signifies the buildability impact of the element in the construction process. Since it could not be measured, a general weighting scale is allocated to this functional attribute of an element.

a) Structural and aesthetic

Any element in the building has a certain function. In some cases the element could also have a combination function, i.e. structural as well as aesthetic. As a default in this approach, a weighting scale was allocated for each of the functional attributes. As a guideline in this approach, any element which has a single function has less weighting scale, than an element which has more than one function. If an element has more than one function, then the weighting scale for each function of the element will be added to derive with the total weighting scale for the element.

The weighting scale of the element is given based on the effect of the element to construction as if it would be decommissioned. For example, alteration of the structure member during construction will obviously affect other elements of the building and could delay seriously the construction progress of the project. If the building element is required due primarily to aesthetic reasons, then the weighting scale of the element will be lower then the structural, since any alteration going will only effect the finished part of the building element. However, if the building element is a structural element and is required to be highly aesthetic then the weighting scale of buildability will be higher than the weighting scale normally used for other structural elements. The same principle also applies to a structural element which is also used as a services element.

6.5.3 Location

The location of the element effects construction work for accessibility of labour, material and plant. Therefore, special requirements would be required to be considered when selecting the resources. For example, if a building element is located on the ground, its method of construction is different to that located on the seventh storey. The principles of evaluating the location factor is related to how easy the resources could be accessible to the element. If special plant, temporary facilities and arrangements are required to realise the element, then the location is critical in the buildability aspect.

a) Horizontal/vertical

Elements situated on a horizontal plane required direct support from falsework or formwork, while vertical elements will require extra strutting and platforms for accessibility of labour or plant. The location of the element, either on the parameter on the inside of the whole building also contributes to buildability.

By determining the horizontal and vertical locations of the elements a weighting scale is applied accordingly. This buildability factor does not have its own buildability score, but the weighting scale assigned for this factor would be used to derive other buildability scores i.e. since location effects the use of plant and facility, its weighting is applied to the use of these resources. A default weighting between 0 - 1 is allocated to these factors. Lower scales represent higher locations or far from the building parameter.

b) **Positioning**

The element position within a floor level i.e. near to floor, ceiling, could also influence buildability. For example ceiling finishes which are located under the floor slab of the floor above, would require a platform for the construction activity compared to floor finishes. The positioning of service ducts on the upper part of the wall would require scaffold when assembled, compared to its positioning at lower parts of the wall.

By determine the position of the element from its geometric location, a weighting scale is applied accordingly. A default weighting between 0 - 1 is allocated to these factors. A lower scale is assigned to higher positions of the element within the floor level. This buildability factor would not have it own buildability score, however the assigned weighting scale is used in other buildability factors i.e. since positioning effects the use of plant and facility, its weighting is applied to the use of these resources.

6.5.4 Trade utilisation

The key concept applied to this buildability element is based on the trades utilisation to construct a building element.

a) Trade usability

The buildability score for trade usability is calculated as percentage from the number of the trades being used for the class of the element. The lower the percentage of usability calculated, the lower the buildability score associated with the element. For example, if tile finishes are widely used on every floor of the building, then it is likely that the same trade will be used for all the work. If floor finishes differ, then different trades would be required for the finishes work.

$$\text{Buildability Score} = 100 * n/\Sigma t$$

where n = number of similar trades used for the element

Σt = total number of used trade

b) Trade variability

The buildability score for trade variability is determined as a percentage calculated from the number of trades required for the element over the total number of trades for the whole class of the element type. Building elements which require a variety of trades are likely to impose various constraints on the preparation works for the construction activities. For example, a wall element made of bricks requires bricklayers. and scaffolders, while concrete wall will require concretor, carpenters, steel fixers and concrete mixers. From these two types of walls different numbers and types of trades are used. Walls which have less interaction and variety of trades indicates good buildability. From the equation, the higher buildability score illustrates higher constraint on construction from trade variability.

Buildability Score = 100 * $\Sigma t / \Sigma tt$

where Σt = total number of used trade

Σtt = total number of trade types

6.5.5 Plant utilisation

This factor reflects the impact of design on the building element from the assembling process based on the usage of plant.

a) **Plant usability**

The percentage calculated to determine the buildability score is similar to the Trade Usability. If the plant is a general plant, then it will carry a lower buildability score as it can be used by other activities. On the other hand, if the activity required specific plant and only occurred at a certain interval o the construction project, then the usability factor for the buildability score would be higher.

Buildability Score = $100 * n/\Sigma p * (W_L + W_P)$

where n = numbers of similar plant used for the element

Σp = total number of used plant

W_L = weighting given between (0-1) based on element location

W_P = weighting given between (0-1) based on element position

b) **Plant variability**

The percentage calculated will depend on the number of plant required to construct a particular building element. The less the variety of plant used to construct the element, the lower the buildability score. For example, concreting activity using a mobile crane, a lorry mixer, and a skip, have higher buildability factor, compared to that of a concreting activity using a small number of plant.

Buildability Score = $100 * \Sigma p / \Sigma pt$

where Σp = total number of used plant for the element

Σpt = total number of plant type

6.5.6 Facility utilisation

The factor is applied to elements which use facilities such as falsework and formwork. The formwork or falsework is divided into two, either a standard formwork/falsework (off the shelve) or traditional formwork/falsework where cutting and assembling activity is required. A weighting scale is assigned to each type. A lower weighting scale is applied to traditional formwork, since a longer time, and more space on site are required to prepare the formwork/falsework, besides the need for carpenters and associated preparatory work, compared to standard supplied formwork. The user/evaluator is given the choice to set the general weighting scale for the formwork/falsework between 0 - 1. A higher weighting scale indicates ease of use of the facilities for the construction.

a) Formwork

If the building element has a complicated shape, traditional formwork is likely to be used. Standard square, round or rectangular shape, with high repetition normally leads to the use of standard supplied formwork. For traditional formwork the buildability factor will therefore be higher. The buildability score is presented as a percentage calculated from the number of elements that could utilise the same form to be constructed over the rest of element class multiplied by the weighting scale given by user/evaluator. A smaller percentage score reflect higher utilisation of the formwork/falsework. therefore showing good influence on buildability.

Buildability Score = $100 - (100 * n/\Sigma n * W)$

where n = number of elements which share similar formwork

Σn = total number of the elements in the class

W = weighting scale (0-1)

b) **Falsework**

The above principle can also be applied to falsework. For example, a number of square floor slabs with similar dimensions can make use of the flying form or table form whereas an irregular shape of floors with varied dimensions will normally require a traditional falsework built on site. The buildability score is presented as a percentage calculated from the number of elements that could utilise the falsework to construct a particular element. over the rest of element class, multiplied by the weighting scale given by the user/evaluator. A smaller percentage score reflects higher use of the falsework and would therefore show a good effect for buildability. The buildability score equation is similar to formwork.

Buildability Score = $100 - (100 * n/\Sigma n * W)$

where n = number of elements which share similar falsework

Σn = total number of the elements in the class

W = weighting scale (0-1)

c) Storage

A traditional formwork/falsework requires fabricating, assembling, and cleaning which has to be stored before being reused, while standard components of formwork/falsework need space only for cleaning, and can be directly used for other elements without conversion or a major alteration. The percentage area allocated on site for storing the formwork/falsework is obtained as the buildability score. The percentage area allocated on a site is based on site layout analysis application.

$$\text{Buildability Score} = 100 * a/\Sigma a$$

where a = storage area

Σa = total storage area

6.5.7 Assembly buildability

This factor represents the conversion factor of the building materials to realise the building elements. It consists of materials, components and sub-assemblies. The lesser the constituent of this factor in a building element, the lower the score of buildability.

a) **Onsite/Offsite**

The terms on site or off site represent whether the building element is likely to be prepared on site from basic materials or ready made in a factory and delivered to site for assembly. If the building element is prepared off site, then the process of construction is made simpler as the element is just required to be assembled into the structure. If on site activities are required to convert the building materials then, other factors such as space, storage, access of plant and labour, etc. will be required. It is therefore likely that an off site approach will give less of a problem on buildability, compared to onsite. A default weighting scale between 0-1 is assigned to both the construction approaches. Lower weighting is allocated for off site methods compared to on site.

$$\text{Buildability score} = 100 * W$$

W = default weighting scale between 0 - 1.

b) **Dry /wet process**

Wet construction processes such as concreting, plastering etc., delays successor activity, requires longer construction time, requires extra resources and space for material conversion, etc. Dry construction processes however, are associated with less buildability impact on construction compared to wet processes. To reflect the buildability impact of these two processes, the user/evaluator would have to set a weighting scale for these processes which are allocated between 0 - 1. A lower weighting scale indicates a higher buildability impact. This buildability factor does not have its own buildability score, but the weighting scale assigned would be used in other buildability factors i.e. process flow factors.

c) Number of assembly

The buildability score of this factor depends on the number of assembly or construction processes required to form a building element, the higher the number of assemblies, the higher the value for the buildability score. For example, a brick wall requires laying bricks and mixing mortar, while a concrete wall requires building formwork, fix reinforcement and concreting. It is obvious that building a wall of concrete will take a lot more resources and time for assembly. To reflect this buildability impact, the buildability score is calculated based on the percentage of number of assembly, for an element over the maximum number of assembly occurring on the same class of element.

$$\text{Buildability Score} = 100 * n/\Sigma ac$$

where n = number of element's assembly

Σac = total number of construction activities of the element.

6.5.8 Element buildability dependency

To form a complete building, all physical building elements have to be connected to other elements. Topological relationship types. represent the relationship between the building elements. The relationship reflects the process or procedure for constructing the elements. For example, supported_by relationship, indicates that the supported element can not be assembled unless the supporting element is built first. Other relationship type such as, attached_to , embedded_in, covered_by, connected_to. etc., all carry a different impact on the flow of construction activity (section 6.3.1.1)

a) Topological dependency

The weighting scale applied to this factor depend on whether the dependent element are structural, services or architectural elements. A building element dependency which is based on structural reason is expected to have the highest weighting scale compared to other elements which have alternative reasons for attachment, such as embedding conduit to a wall or floor, etc. Other relationships such as attached_to, embedded_in. or covered_by range from low, moderate, to a high buildability weighting scale.

The allocation of this scale depends on whether the dependent element is an architectural, structural or the services element. For example, an architectural element of a plaster finish which is attached to a partition wall should have a higher weighting to that services element, which could be attached to other elements. The weighting scale assigned to this buildability factor would also be used to calculate other buildability scores i.e. process flow. The topological buildability score is calculated as follows:

Buildability Score $= 100 * (W1 + W2....+) / \Sigma nR$

where ΣnR = total number of elements relationship

W = weighting scale (0 -1) for each element associated with the dependent element

b) **Process relationship type**

The factor defines whether the successor and the predecessor of the construction activities are wet and wet, dry and dry, wet and dry, etc. For example, concreting a slab is a wet process. Since concreting is a wet process. a certain amount of time has to be allocated to let the structure hardens before another successor activity can commence. However, if the element required a dry process in both succeeding and predecessor activities, the construction work can continue without interruption. Therefore, dry and dry relationships would show a low buildability score, while wet and wet has high score for buildability. Both weighting scales for the processes are added and multiplied by a 100 to obtain the percentage. Higher buildability scores would indicate that the element would take a considerable time to build.

$$\text{Buildability Score} = 100 - (100 * (Wp + Ws.. +) / \Sigma nR)$$

where Wp = average weighting factor between 0-1 for predecessor activity

Ws = average weighting factor between 0-1 for successor activity

ΣnR = total number of elements involved

c) **Trade flow relationship**

From the developed construction plan, all the construction activities and the required resources are interconnected based on the dependency factors. If different trades are required between the predecessor and the succeeding activities of an element, then the factor of buildability is high. On the other hand, if the same trade is used to construct the succeeding element, then the buildability impact would be low since there is a continuation of trades usage. The buildability score is determined by calculating as a percentage the number of similar trades to be used for both successor and predecessor activities, divided by the total number of trade for both activities.

$$\text{Buildability Score} = 100 - (100 * \Sigma t/\Sigma ac)$$

where Σt = total number of similar trade

Σac = total number of trade used by both construction activity

d) **Plant flow relationship**

The same principle applied for a trade flow relationship will be used for the plant flow relationship.

$$\text{Buildability Score} = 100 - (100 * \Sigma p/\Sigma ac)$$

where Σp = total number of similar plant

Σac = total number of plant used by both construction activity

6.6 The framework for the evaluation

Each of the buildability elements described above only represent part of the buildability aspects on the design solution. A sum of all the buildability scores obtained from each of the buildability elements will produce the buildability index. Higher buildability scores or buildability index when calculated, represents less consideration of buildability on the design solution. Comparisons can be made with other similar building elements by comparing their buildability score and buildability index.

If a line graph is used to represent each of the buildability scores accounted from the analysis, then the number of lines represented on a graph will indicate the range of differences of a buildability index analysed from similar building elements. When this evaluation method is conducted on similar building elements in an iterative manner using different design specifications and attributes, the result can illustrate the impact of these changes on the scale of the buildability index and the buildability score. A table summarises the methods of calculation for each of the buildability elements, the buildability score, and the buildability index as presented in Table 1.

BUILDABILITY FACTORS	Weighting	Calculation	Buildability Score
Dimensional	nil	$100 - (100 * n/\Sigma n)$	x
Material	nil	$100 - (100 * n/\Sigma n)$	x
Assembly	nil	$100 * n/\Sigma ac$	x
On/Off site methods	W(0-1)	$100 * W$	x
Plant Flow	nil	$100 - (100 * \Sigma p/\Sigma ac)$	x
Plant Usability	W(0-1)	$100 * n/\Sigma p * (W_L + W_P)$	x
Plant Variability	nil	$100 * \Sigma p/\Sigma pt$	x
Process Flow	W(0-1)	$100 - (100 * (Wp + Ws)/\Sigma nR)$	x
Specification	nil	$100 * n/\Sigma n$	x
Shape	W(0-1)	$100 -(100 * W)$	x
Storage	nil	$100 * a/\Sigma a$	x
Element Functionality	W(0-1)	$100 * W$	x
Topological Dependency	W(0-1)	$100 * (W1 + Wn....+)/ \Sigma nR)$	x
Trade Flow	nil	$100- (100 * \Sigma t/\Sigma ac)$	x
Trade Usability	nil	$100 * n/\Sigma t$	x
Trade Variability	nil	$100 * \Sigma t/\Sigma tt$	x
False/ Formwork Utilisation	W(0-1)	$100 - (100 * W * n/\Sigma n)$	x
		Buildability Index =	Σx

Σn = total number of elements

Σac = total number of activity

Σp = total number of used plant

ΣnR = total number of element relationship

Σpt = total number of plant type

a = storage area

n = number

W = weighting factor

W_L = weighting location

W_P = weighting positioning

Wp = weighting factor for predecessor activity

Ws = weighting factor for successor activity

Σa = total storage area

Σt = total number of used trade

Σtt = total number of trade type

Σx = total score of buildability

Table 1: Table showing the buildability factors and the calculation for buildability scores and index for each building element.

6.7 Summary

This chapter has described the qualitative aspects of buildability improvements and outlined the quantitative approach for evaluating the key aspects using construction information. Based on the explanations given, the proposed methods of formalising the construction data and the buildability evaluation approach are outlined. Chapter 7 will propose the information models of the domains while Chapter 8 describes the framework of the integrated system. The implementation of the information models in the integrated computer environment will be described in Chapter 9.

Chapter 7
Proposed information models for construction planning and buildability evaluation

7.1 Introduction

Galle (1995) noted that modelling the design and construction processes is a difficult task. The difficulty is caused by the complex processes involved in the construction industry which has various aspects of information interrelated between the participants concerning the product (Howard *et al.*, 1989; Gallies, 1991; Eastman & Fereshetian, 1994; Bjork, 1992; Turk, 1992 & 1994; Aouad *et al.*, 1993; Alshawi & Faraj, 1995, Alshawi & Underwood, 1996).

In order to develop the information models for the construction planning and the buildability evaluation applications, it is important to clearly define the scope within which these two domains interact with other domains over a project life cycle. The modelling process would require a modelling technique that could support complexity, reliability, design capability, flexibility, speed of development and ease of change.

This chapter discusses the object oriented technique for information modelling, its key concepts, and then presents the proposed information models for construction planning and buildability evaluation.

7.2 The object oriented techniques

An early appreciation of 'objects' in information modelling can be traced back to the SIMULA language (Birtwistle, 1979) in the late sixties. The involvement of those researchers working with this language introduced the first object oriented programming language which was based on the notions of messages and activities known as Smalltalk. Gradually by the seventies, the notion of 'classes' which encapsulates both the state and behaviour of entities was developed as an important part of the language.

From this point onward, the programming languages, the artificial intelligence and the databases have contributed independently to the development of the conceptual modelling (Rolland & Cauvet. 1992). Since then, gradual and diverse changes have occurred in the information modelling and programming metaphor. The database design which typically emphasised static properties radically differs from the programming languages view which emphasises the dynamic properties of the data structure. This separation could easily lead to a cumbersome, inflexible and problematic process of system development. Further advances in conceptual modelling is required and essential to integrate the concepts, tools and techniques, for system specifications (Rolland & Cauvet, 1992). It is clear from this point that both structural and behaviour properties of application objects must not only be designed, but integrated and implemented.

Various researchers have reviewed different types of modelling techniques, e.g. the well known process oriented methods such as SASD (DeMarco, 1978), SADT (Ross & Schoman, 1977), JSD (Jackson,1983), SSADM (NCC, 1990) and data driven methods ER (Chen, 1976), NIAM (Nijssen & Halpin, 1989) and others (Eastman & Fereshetian, 1994; Van Nederveen, 1993; Turk, 1992; Bjork, 1992). However, most of these modelling techniques imply a separation between the data, and processes performed on the data, besides only one perspective can be represented in a model (Ford *et al.,* 1994).

Since the object oriented modelling methodologies reached their maturity in the 1990's, the methodologies have been emphasised as being the most popular technique to model complex information (Ahmed *et al,* 1991; Turk, 1992; Alshawi & Underwood, 1996). The object oriented techniques which consist of analysis, design and programming, present a new unifying approach in information modelling since the dynamic and static models of information are defined from a single process technique of object analysis and design (Martin, 1993; Rolland & Cauvet. 1992; Fiadeiro *et al.*, 1992). Features such as abstraction, encapsulation and inheritance which simplify the design of complex systems make these techniques one of the most powerful techniques for software development (Elzarka & Bell, 1995;

Martin,1993). The techniques model the world in terms of objects that have properties and behaviour, as well as events that trigger various operations which change the state of the objects.

7.3 The advantages of object oriented techniques.

Fenves (1989), Turk *et al.,* (1994), Alshawi & Underwood, (1996), Yamazaki (1994), Aouad *et al.,* (1993) suggested that object oriented techniques are essential for modelling various disciplines in the construction industry. The object oriented product models can be very useful and powerful for sharing and maintaining the project data from design to planning and construction (Ito, 1993).

Although the definition of object oriented application is still a matter of controversy in the computer science community (Sause *et al.,* 1992, King, 1989), there are various aspects of information modelling in object oriented techniques which make it more advantageous than others. Among the advantages featured of object oriented techniques are its uniform modelling methodology of static and dynamic phenomena (i.e. integrate both structural and behavioural aspects of object in a single modelling technique), uniform modelling of system and environment (i.e. conceptual modelling is not exclusively concerned with the development of a computerised information system) and reification and integration (reuse) (Fiadeiro *et al.*, 1992).

King (1986) also describes fundamentally object oriented models as having three advantages over traditional hierarchical, network and relational models. First the data models can be viewed as a collection of abstract objects, rather than a set of interrelated or flat tables. Secondly, object oriented models support explicit constructs for representation abstraction (or attribute interconnections) and generalisation (or subtyping). Lastly an object oriented schema more easily captures integrity constraints, in particular, attributes of abstract objects can be viewed as functions.

Besides object oriented information modelling techniques providing many important features such as inheritance, encapsulation, interaction by means of messages, Martin (1993) suggested that other advantages can be benefited from this technique including reusability (classes are designed so that they can be reused in many systems), reliability (software developed from well proven stable classes is likely to have fewer bugs than software created from scratch), faster design (applications can be created from pre-existing components), integrity (data structures can be used only with specific methods), more realistic modelling (Object oriented analysis models the application area in a way that is closer to reality than conventional analysis), interoperability, etc.

The object oriented techniques also provide a better paradigm and tools for describing and modelling practical problems as close to the user's perspective, constructing reusable software components, easily extensible and modify (Munns *et al.*, 1994). Ahmed *et al.,* (1991) noted that the advantages of object oriented techniques are that they enable more realistic data models, provide powerful unified knowledge representations, enable easier schema development, better support for co-operative work, etc.

7.4 Object oriented methodologies

There are many object oriented methodologies, which can be utilised to model the information of a particular domain, to name the few, Booch (1994), Coad & Yourdon (1991), Martin (1993) and Rumbaugh *et al.* (1991). Many of these object oriented techniques share the same concepts for modelling information (i.e. concepts and rules for using them. and associated specification language, a process by which to construct the information system, etc.), however some techniques claim to be more powerful than others (Cribbs, *et al.*, 1992). It is outside the scope of this study to evaluate these methodologies, however detailed reviews of the various object oriented methodologies can be found in Cribbs, *et al.*, (1992). and Underwood (1995).

This study has adopted Martin (1993) object oriented methodology for modelling the information of a construction planning and buildability evaluation. This methodology was selected because it has clear diagramming conventions, expressive notations and the ability to deal with process and event oriented domains such as that of planning and buildability evaluation. As similar to other object oriented methodologies, the development of information modelling in Martin (1993) methodology is governed by the main concepts of object oriented technique which are :-

7.4.1 Object and object type

An *object* can be considered as anything, whether it is real or abstract. Object may also refer to other entities such as an attributes, classes and event or processes involved within the object. A category of objects which represents an abstraction of the objects is called *object type*. The *object type* specifies a family of objects without stipulating *how* they are implemented. Hence, an *object type* can be defined as a set of objects that share a common structure and common behaviour. *Object types* are important because they create conceptual building blocks for the system. When implemented in an object oriented language, *object types* are transferred into *classes*. Figure 7.1 illustrates two object types a Wall and a Column.

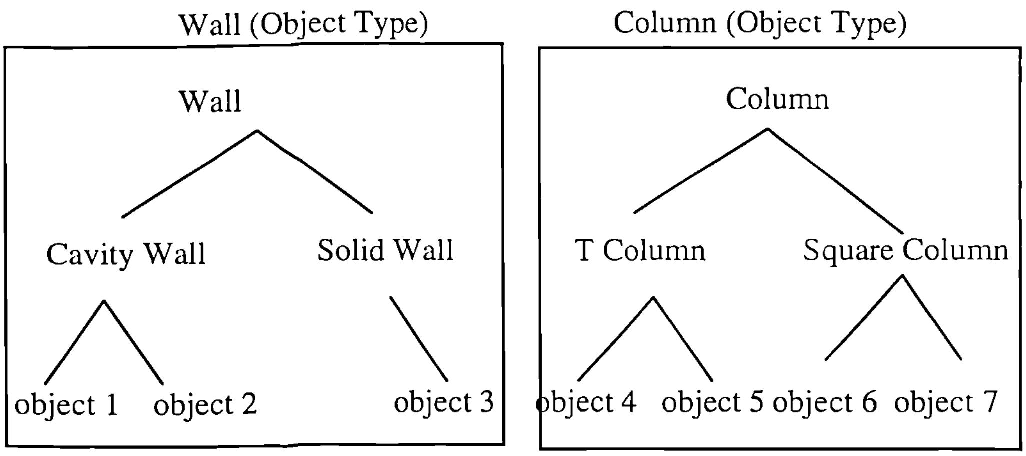


Figure 7.1 Objects and object type

For every single object, three kinds of properties exist, i.e. the state, the behaviour and the identity of the object. The state of the object describes the dynamic and the static properties which are related to the object. The behaviour shows how an object acts upon another object which may include changing of state or action. While the identity of an object reflects the property of an object which distinguishes the object from other objects. By categorising objects according to their type or class, a mass of procedures, knowledge and behaviour about the object can be written within that specific category objects. This advantage allows a complex problem domain to be divided into a smaller category where specific solutions can be delivered.

7.4.2 Attributes, methods, messages and polymorphism

An object normally has *attributes* which describe the properties of the object. The values of the attributes define the local state of the object. Figure 7.2 illustrates an object Column with its attribute's type and values. Objects can also have their attribute's values changed, by sending a request or a *message* from another objects or activated the *method* encapsulated in the object. A collection of methods within an object defines the behaviours of the object. Polymorphism however, refers to the ability of two or more object types to respond and utilise a similar request or *message* within its own context (Martin, 1993).

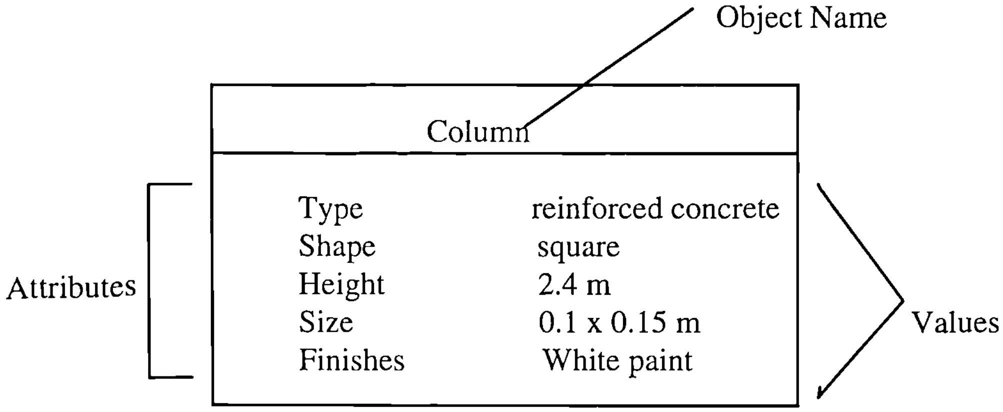


Figure 7.2 Column Object and its attributes.

7.4.2 Encapsulation

Encapsulation is the concept of hiding the object's attributes and methods behind the message interface. Encapsulation is provided by defining methods for objects. By sending a message to an object, the methods encapsulated within that object are triggered off without the users intervention. Encapsulation supports system modifiability since an object can be totally changed without affecting the remaining system. Encapsulation also supports modularity since it provides explicit barriers among different abstractions. New objects can be added without disturbing an existing system (Fenves, 1989).

7.4.3 Hierarchy and inheritance

Hierarchy is an approach used to define objects into groups of related levels of abstractions. The hierarchy increases the semantic content of individual chunks of information by explicitly distinguishing the distinct properties of different objects. The two most common approaches to defining hierarchies in a complex system includes part-of and kind-of hierarchies. By establishing the hierarchy of an object class, the attributes and methods defined in the parent object can be inherited by the child objects. Inheritance thus represents a hierarchy of abstraction in which a subclass inherits the attributes from one or more superclasses.

There are two types of inheritance either single inheritance or multiple inheritance. For a single inheritance, a class can inherit data structure and operations of one superclass, while in multiple inheritance a class can inherit from more than one superclass.

7.4.4 Instances

Instance is a single object that is created from a member of the *object type*. The instance would inherit all the attributes of the parent and also would have values unique to represent itself.

7.5 The object structural analysis (OSA) and object behaviour model (OBA)

To apply Martin's (1993) object oriented methodology for modelling information of the construction planning and buildability, two types of analysis are required; the Object Structural Analysis (OSA) and Object Behaviour Analysis (OBA).

The Object Structural Analysis (OSA) is performed to produce the *object structure model* of a domain area which describes the domain's object types and its structure. The objects are generated by means of decomposition of the problem area according to the real world structure of the application domain. The model provides most of the static information about a particular domain area such as their object types, their associations (class), specialisation, generalisation and composition. The *object structure model* is represented in the *Object Structure Diagram.*

To model the dynamic aspects of the object, the Object Behaviour Analysis (OBA) is carried out. It produces *object behaviour model* for the domain which represents the behaviour associated with the objects. The purpose for modelling the behaviour of objects is to provide a conceptual formalism for expressing how and when changes occur to objects.

In modelling the behavioural aspects of the domain, one is interested in specifying the interaction of the applications with its environment, the input and output of each process, the sequencing of the process, etc. Such behaviour is represented by the *Object Flow Diagrams* and/or *Event Diagrams.* The notations and diagrams for both OSA and OBA used for information modelling in this study are explained in the following subsections.

7.5.1 The notations

There are several type of notations and diagrams applied in Martin's (1993) object oriented technique i.e. Object Flow Diagram, Object Structure Diagram, Fern Diagram, etc. These graphical notations are used to illustrate the object, object type, relationship, cardinality, composition, and processes. Figure 7.3 shows a notation for the Object Flow Diagram, which includes a round-cornered box to represent activity while the 3D box represents the object which is produced by the activity. The arrow indicates the flow of the object into or from an activity.

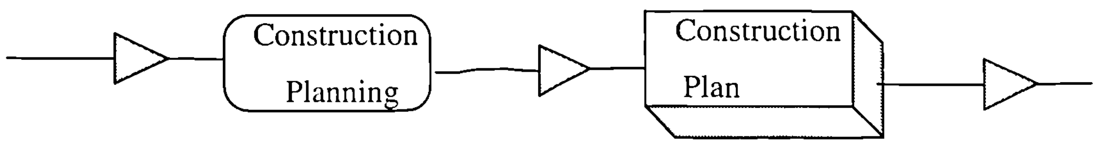


Figure 7.3 Object Flow Diagram

Hierarchical abstraction of objects can be represented either by a fern diagram or a box diagram. The fern diagram refers to a network structure which shows the sub type objects of more than one super type (Martin, 1993). Objects which are defined at the further left hand side normally represents a general object, than at the furthest right hand side. Figure 7.4 is a fern diagram which illustrates the object Ground Works which has three subtypes. They are the 'Ground Excavation', 'Remove Soil' and 'Compact Soil'.

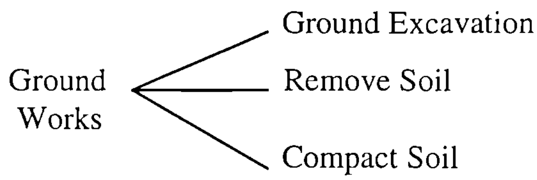


Figure 7.4 An example of a fern diagram.

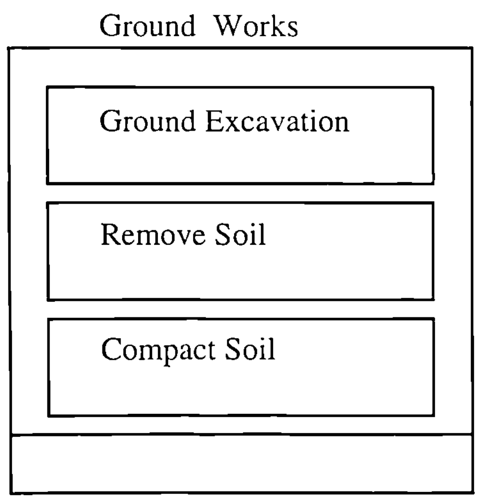


Figure 7.5 An example of a Box Diagram

When using a box diagram to represent hierarchical abstraction, each of the objects 'Ground Excavation', 'Remove Soil' and 'Compact Soil' would be placed in a box within a box for 'Ground Works' object, as shown in Figure 7.5. This diagram is only suitable for a small number of object types, since they can easily become complex.

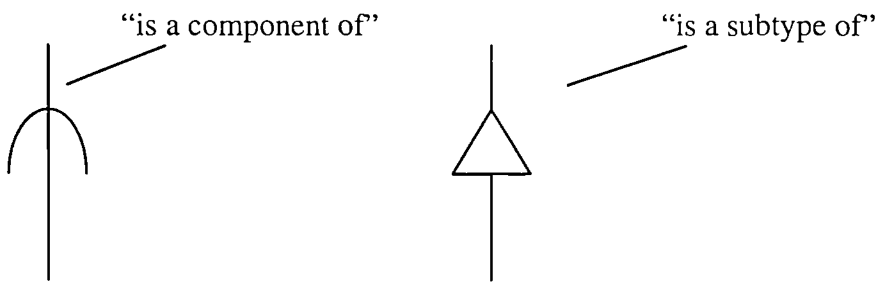


Figure 7.6 Composed_of and generalisation (or sub typing) and notations (Martin, 1993).

Since objects can either be a component_of, or a sub_type of another`s object, there are two kinds of hierarchical diagrams in Martin (1993) to reflect these relationships, i.e. composed_of and sub_type (generalisation) relationships. To represent a composed-of relationship, a line with 'C' symbol is used (Figure 7.5). The 'C' symbol is directed towards the composed object.

For generalisation, a line with a triangle arrow is used (besides the box diagram) to show the sub type relationship (Figure 7.6). Figure 7.7 illustrates a level of sub type relationship using a line and triangle arrow which implies that Ground Excavation or Remove Soil are Ground Works.

The cardinality constraint between objects is required to establish the scope of the relationship, e.g. one-to-many, one-to-one, zero-to-one, zero-to-many, etc. Figure 7.8 illustrates the cardinality constraint symbols.

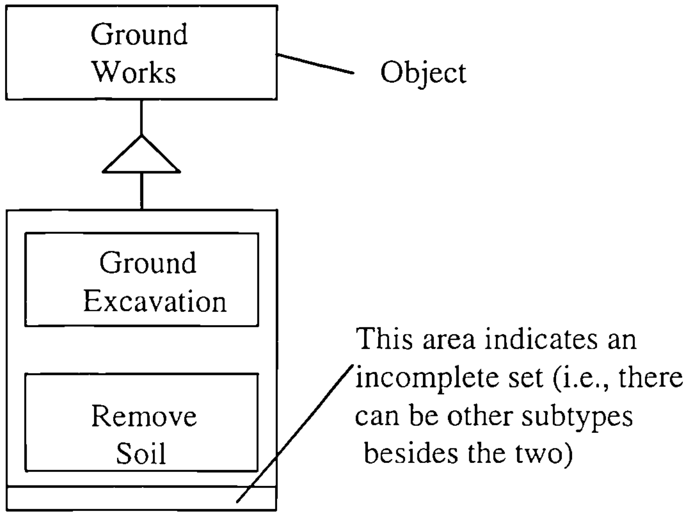
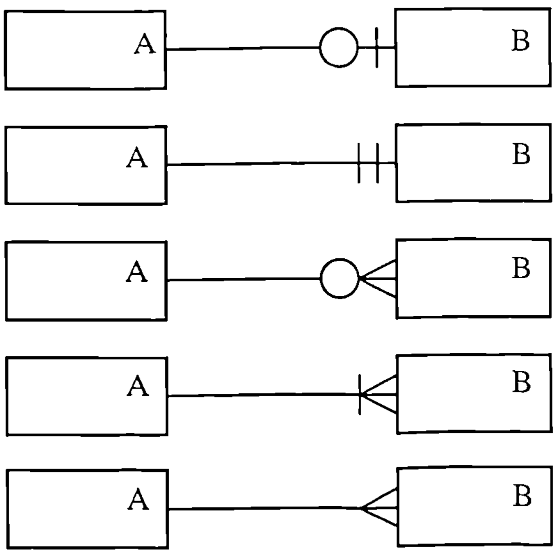


Figure 7.7 Example of a subtype relationship



Each Instance of A is Associated with How many Instances of B?

0	1
1	1
0	More than 1
1	More than 1
More than 1	More than 1

Figure 7.8 Cardinality-constraint symbols (Martin, 1993).

For one-to-one cardinality, a small bar across the line is drawn, and for zero or one, a zero symbol is placed with a small bar across a line. To represent a zero-one or many relationship, a zero symbol and the crow's feet is drawn between the objects. For representing one to many relationship, a crow's feet connector is drawn between two objects. An example of a one to one or many relationship is illustrated in Figure 7.9.

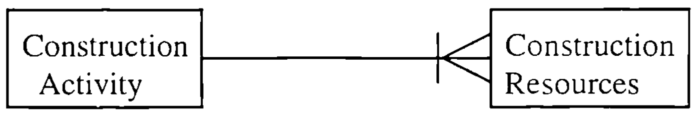


Figure 7.9 An example of one to many relationship.

7.6 The proposed information models

Following the principles of a construction planning process and the proposed buildability evaluation described in Chapter 2, 3 and 6 the application data models have been developed to represent both construction planning and buildability evaluation domains.

The developed object flow diagrams of the domains representing the process models while the object relationship diagrams represent the domain's application data model. Besides providing the information requirements for construction planning and buildability evaluation, the proposed data models were also developed to serve all other construction applications within the Integrated Construction Environment (ICE) such as estimating, interim valuation, site layout planning, plant selections, etc.

The process models were first developed and represented by the object flow diagram (OFD). The highest level of object flow diagram represents the main process involved in the construction planning process and those of buildability evaluation (Figure 7.11). The diagram shows several processes and their products which are involved to satisfy the information exchange requirements of the construction planning process and the buildability evaluation with other disciplines.

From this highest level object flow diagram, two object relationship diagrams and object flow diagrams were produced. Figure 7.10 below illustrates how each of the developed type diagrams (OFD and ORD) are related to each other. Two OFD`s were developed for the two activities (i.e. 'The 'Produces Construction Plan' and 'Provides Buildability Evaluation') Figure 7.12 and 7.14. These diagrams specifically highlight the information requirement for those two activities.

Two other object relationship diagrams (ORD) were developed to model the object involved in the above two OFD`s. They highlight all the static objects and their relationships as shown in Figure 7.13 and 7.15.

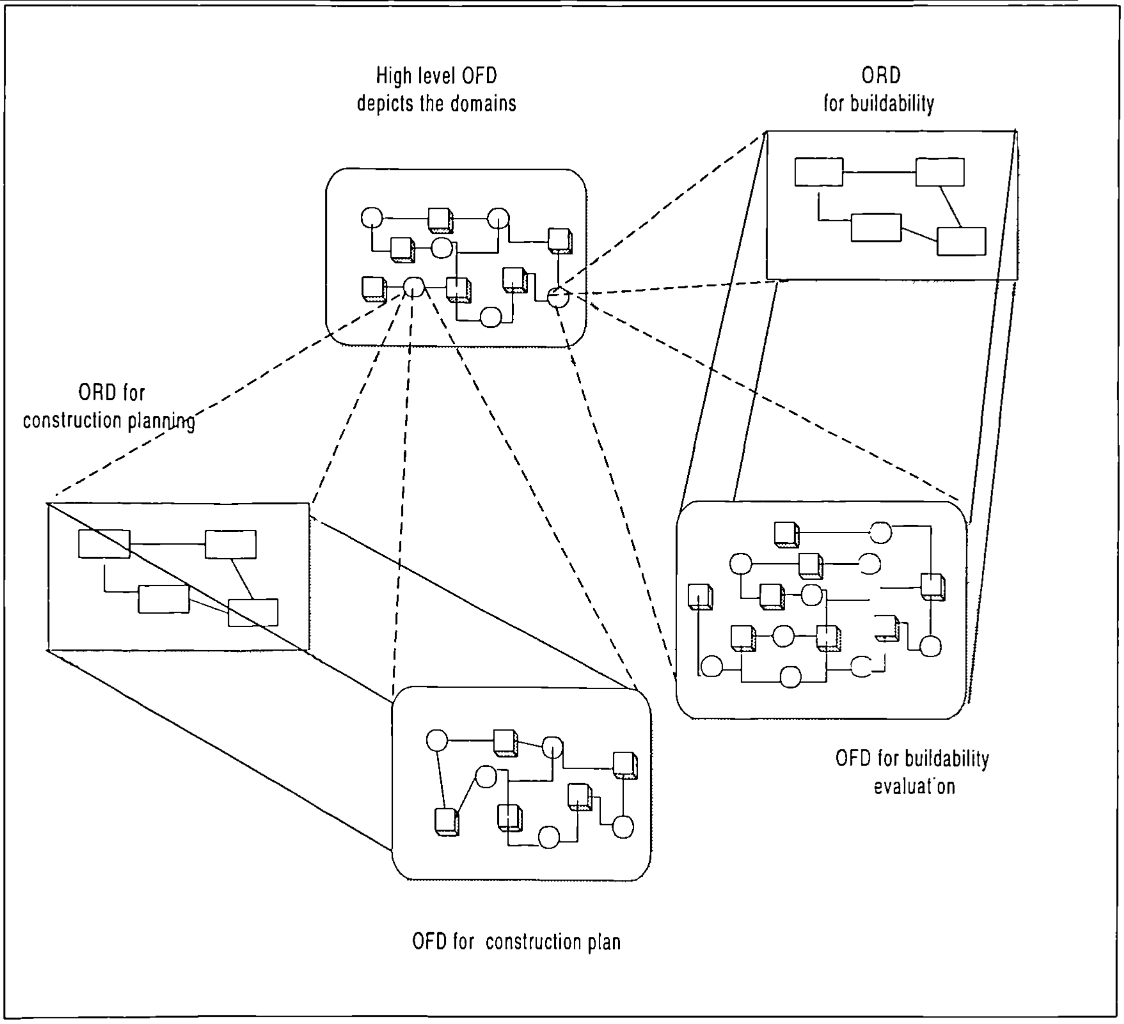


Figure 7.10 Relationship between the different levels of object structure diagram and object flow diagram.

7.6.1 The object flow diagram for construction planning process

To illustrate the central role of construction planning process in sharing, using and generating most of the construction information, a high level object flow diagram representing the initial information exchange processes was developed as shown in Figure 7.11. The diagram illustrates the initial stage of construction planning processes which mainly focus on gathering information to be delivered for the final plan. From the object flow diagram, six agents (i.e. Project Manager, Estimator, Material Manager, Plant Manager and Site Manager) are involved in the exchange of construction information for the construction planning process. Each of the agents receives and produces specific information in order to assist the Construction Planner who produces the construction plans. The large shaded areas on the diagram highlight the scope of other main applications within which the construction planning domain interacts.

The production of the construction plan starts when a construction planner receives the drawings, specifications and the bill of quantity of a project. The object 'Specification, Drawings, and BQ' must provide all the necessary information, i.e. Architectural, Structural and Services drawings, which are required by the planner to propose an initial construction plan. The 'Construction Planner' identifies the type and the amount of construction works and their associated resources.

The knowledge of the 'Construction Planner' is required at this stage in order to produce the activity types and their breakdown as well as to provide information on the technology required to execute the various activities. To communicate the initial outline plan to other disciplines, the planner 'Produces Activity and Resource Plan', 'Proposes Construction Plan' and 'Proposes Plant For Construction Activities'.

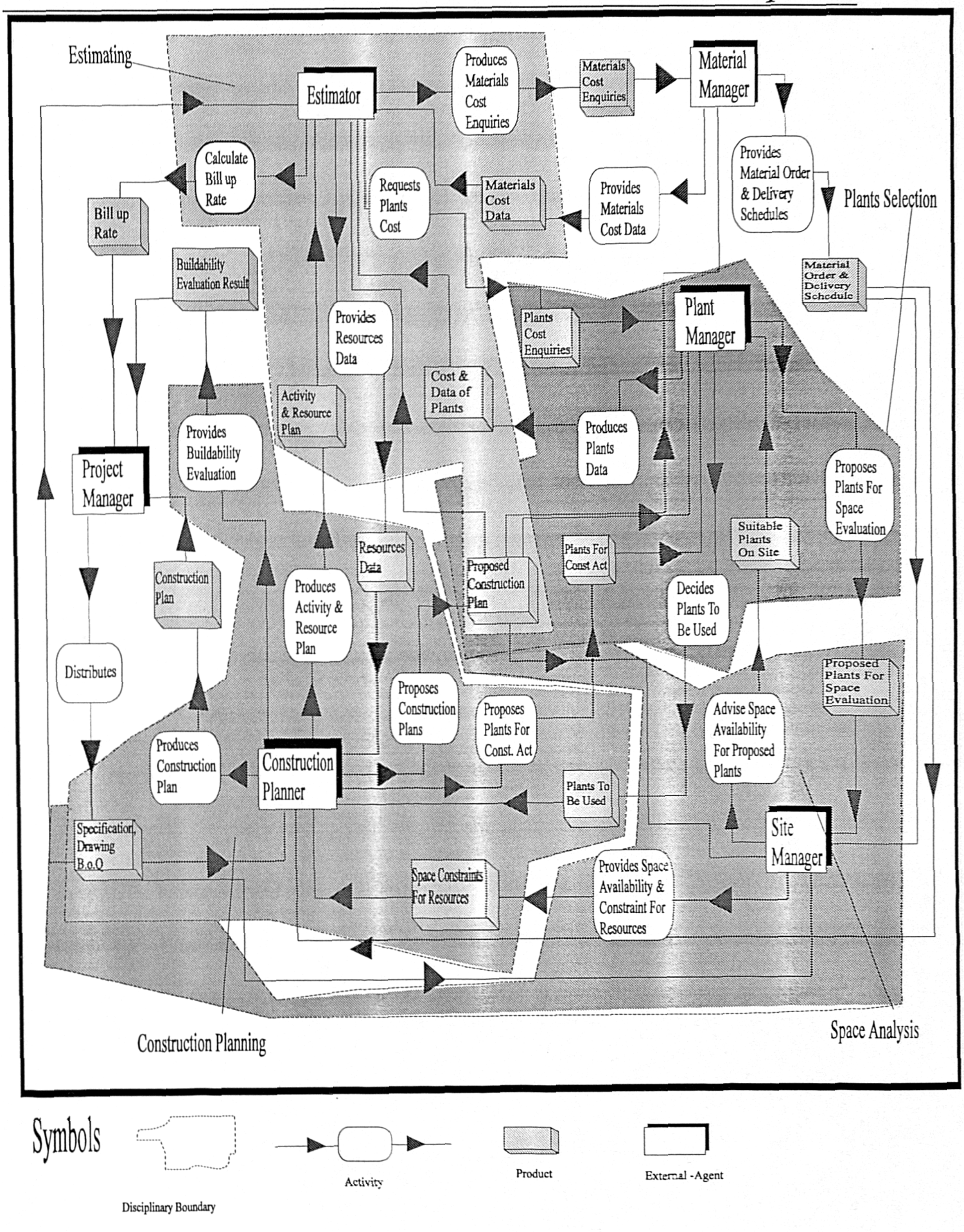


Figure 7.11 A high level object flow diagram representing the initial stage of information exchange for construction planning.

In order to examine the efficiency of the outlined plan, and to remain consistent with other disciplines, the outputs of these three processes are sent to other agents to check for suitability and to obtain other information such as costs, resources and the construction methods to be applied. For example, the output of the 'Proposes Construction Plan' process i.e. the 'Construction Plan' is sent out to the 'Material Manager' who determines the availability of the selected materials and produces material orders, delivery times and schedules. This information is then fed back to the 'Construction Planner'. Meanwhile, the output of the 'Produces Activity & Resource Plan' process i.e. 'Activity & Resource Plan' is sent out to the 'Estimator' to produce resources data and to calculate the bill up rates, as shown in Figure 7.11.

The 'Estimator' returns 'Resources Data' back to the 'Construction Planner'. On the other hand, the 'Plant For Construction Activities' is sent together with the 'Construction Plan' to the 'Plant Manager' who 'Proposes Plant For Space Evaluation'. The output of the later processes i.e. the 'Plant For Space Evaluation' is sent to the 'Site Manager' who approves the availability of space for such plant at the required time. Once the 'Suitable Plant On Site' is received by the 'Plant Manager', the 'Plant Manager' informs the 'Construction Planner' with the 'Plant to be used'.

Once the final decision for the plan has been agreed by all relevant parties, the 'Construction Planner' then 'Produces Construction Plan'. Figure 7.12

depicts the object flow diagram decomposed from the 'Produces Construction Plan' process. When all the necessary information is available to develop a final construction plan, the 'Construction Planner' then 'Determine General Activity' for all the elements designed for the facility. For example, Construct Ground Beam-1, Install Window-1, etc. These names represent the 'Elemental Construction Activities' object. From these representations, various 'Construction Workpackages Activities' and 'Construction Tasks' are then produced by decomposing the elemental construction activities. At this stage, the building element specifications and attributes are referred to arrive with correct construction work packages activities and their construction tasks.

Once the 'Construction Tasks' are established, each of them will be allocated with the basic number of resources according to the agreed construction method. Calculations of the duration of such tasks are based on the productivity of unit plant and labour and are then aggregated upwards to establish the duration for the 'Elemental Construction Activities'. Based on the various dependency factors, all the 'Construction Tasks' and 'Construction Workpackage Activities' are linked accordingly.

If more resources and spaces on site are available, the 'Elemental Construction Activities' can be grouped accordingly into a higher representation i.e. a 'Construction Milestone Grouping' activity. Again, based on the availability of resources and the space, the 'Construction

Milestone Grouping' activities are grouped to represent higher levels of construction activities such as 'Construction Divided in Zones' and/or 'Construction Divided in Phases'.

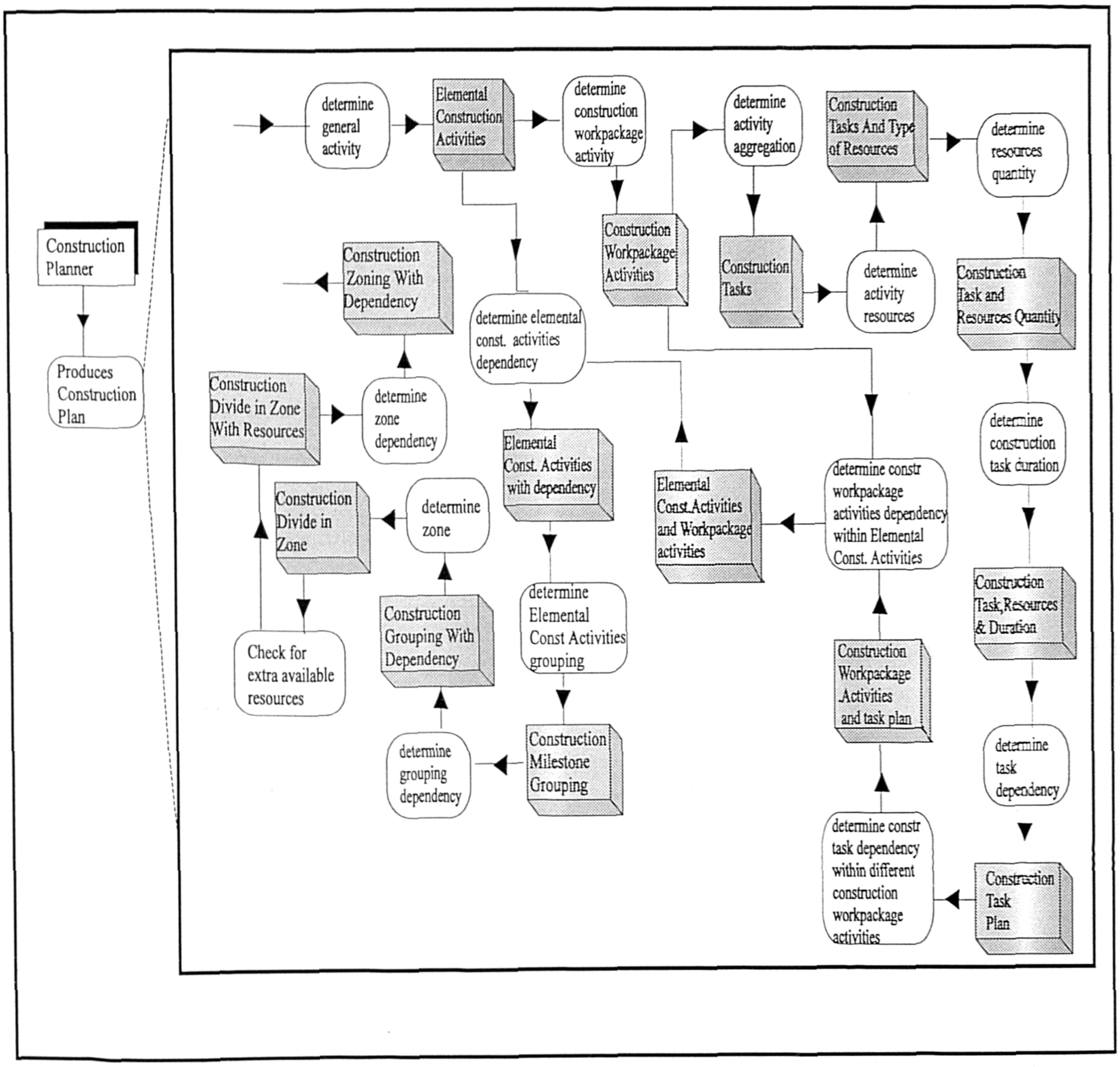


Figure 7.12 The decomposition of 'Produces construction plan' process

The dependency for each of the 'Construction Milestone Groupings' are then established before aggregated upwards and become the components of the higher representation of construction activities.

7.6.2 The object relationship diagrams for construction planning

Figure 7.13 illustrates the main objects involved in construction planning along with their relationships. The 'Construction Activities' object is shown at the centre of the diagram where it is linked to 'Dependency Factors', 'Construction Methods', 'Construction Resources', 'Building', and 'Construction Space'.

The 'Building' object, at the left hand side of the diagram, is realised by the 'Construction Activities' object. It consists of a building type, building systems, building elements, building components and its materials, each of which has type and specifications. The 'Building Elements' object is realised by the 'Construction Activities' object and has a one to many relationship with it. The cardinality of this relationship depends on the number and type of 'Building Components' and 'Building Materials' that exist in the building elements.

The 'Building Materials' will also be used at the later stage by the 'Construction Activities' to form the building components and the elements. Since, the 'Construction Activities' object depends on the building element components and it`s material compositions, various sub type activity objects exist, such as 'Moulding', 'Concreting', 'Formworking', 'Bricklaying', etc.

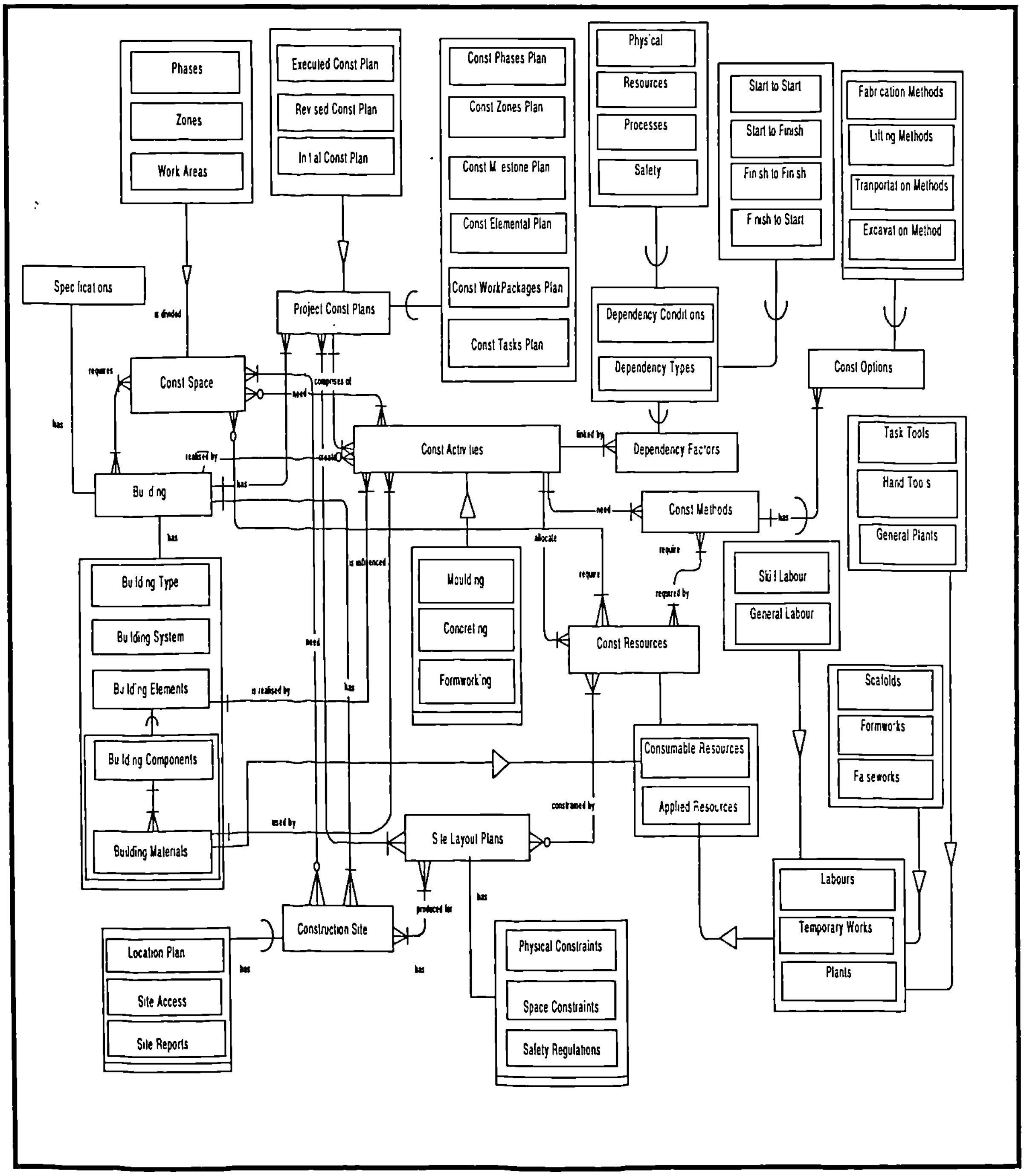


Figure 7.13 Object relationship diagram (ORD) for construction planning.

To execute the construction activities, the processes require the 'Construction Methods'. For the 'Construction Activities', the 'Construction Methods' may involve one or many. Since there are various options, the 'Construction Method' required has to be selected from the available 'Construction Options' i.e. 'Construction Methods' can have one or many options from which to choose. The range of the 'Construction Options' can be the fabrication methods, lifting methods, transportation methods, excavation methods, etc.

The selection of a suitable construction method is based upon the contractor's experiences and the availability of the resources. Each of the selected 'Construction Methods' normally requires one or many 'Construction Resources' such as plants, labour, materials and temporary works i.e. scaffolding, formwork, and falsework. Where a 'Construction Resources' object can be utilised by one or many 'Construction Methods', these two objects, i.e. 'Construction Methods' and 'Construction Resources', have to be considered simultaneously in order to achieve consistency: construction methods have to be selected according to the availability of resources and its suitability to site. This is an issue which has to be considered if construction options and resources are to be kept in two different databases at the implementation stage, which is most likely to be the case.

There is a zero to many relationship between 'Site Layout Plans' and 'Construction Resources'. The 'Site Layout Plans' represents the site plans at various stages of the construction process and shows the type, location, and quantity of the required resources. 'Site Layout Plans' allocate one or many 'Construction Resources' on the plans and therefore can impose many physical constraints, space constraints, and construction site regulations with respect to the usage of resources.

One or many 'Site Layout Plans' can be produced for one or many 'Construction Sites'. 'Construction Sites', which can have location plans, site access information, and site reports, has one or many construction 'Space' and can have one or many 'Building' projects. The 'Space' object, which is the space required by an activity or a resource, needs zero or many 'Construction Site'. For example, a construction activity such as off site fabrication of reinforcement does not need a space on the construction site. contractor/client offices may not need to be on the construction site itself, etc. The 'Space' object is divided into working areas, zones, and phases according the usability of resources within the available space. The 'Building' project has a one to many relationship with 'Space'.

The relations between 'Construction Activities' are determined by 'Dependency Factors'. The 'Dependency Factors' object consists of dependency conditions, i.e. physical conditions, resources limitations. processes flow and safety, and dependency types, i.e. start to start, start to finish, finish to finish, finish to start. For example, between a beam and a column there is a physical dependency relationship which records that beams are supported by columns. From this dependency relationship, any physical element which is supported by another element cannot be constructed unless the supporting element is first constructed. In the case of resources, the dependency is established when more than one activity share similar resources. The resources to be shared can be of any type from labour, plant, temporary facilities to space.

For process dependency, the relationship is governed by the element construction technology. For example, for a concrete column to be constructed, the reinforcement has to be in place before form work and concreting activities proceed. In terms of the safety relationship, the space and the conditions of the working area, which are also governed by regulations, determine whether other supporting construction activity is required to be performed before the actual construction activities for that element are carried out. The main data sections, i.e. ‘Dependency Factors’, ‘Construction Methods’, ‘Construction Resources’, ‘Building’ and ‘Space’, define the construction activities and their required relationships and resources which in turn can be used to generate the 'Project Construction Plans'.

The 'Project Construction Plans' object has a one to many relationship with 'Construction Activities' while the latter has a one to one relationship with 'Project Construction Plans'. 'Project Construction Plans' may be elemental construction plans, construction work packages, construction task plans, construction milestones plans, construction grouping plans, or construction zones plans. Each of these plans displays a different level of information about the construction process and therefore uses different types of information. 'Project Construction Plans' can either be an execution construction plan, revised construction plan, or initial plan. Each of these types of plans present different types of information at different stages of the construction process.

7.6.3 The object flow diagram for buildability evaluation

Once the 'Construction Plan' is completed, the construction information available in the plan and those from the 'Specification, Drawings, and BQ' can be used to present the 'Buildability Evaluation Result' to the 'Project Manager'. The process 'Provides Buildability Evaluation' in Figure 7.11 determines the various measurements applied to derive the 'Buildability Evaluation Result' report. Figure 7.14 represents the decomposition of the 'Provides Buildability Evaluation' process.

There are eleven major processes which provide the 'Buildability Evaluation Result'. These are 'Determine Shape Repetitiveness', 'Determine Dimensional Repetitiveness', 'Determine Material Repetitiveness', 'Determine Assembly Difficulty', 'Determine process Difficulty', 'Determine Plant Dependency', 'Determine Plant Usability', 'Determine Plant Variability', 'Determine Topological Dependency', Determine Trade Usability' and 'Determine Trade

Variability'. Each of these processes provide different information which are required in the 'Buildability Analysis Report' as described in Chapter 6. Each of these processes use different types of construction and design information when evaluating the buildability aspects of the design.

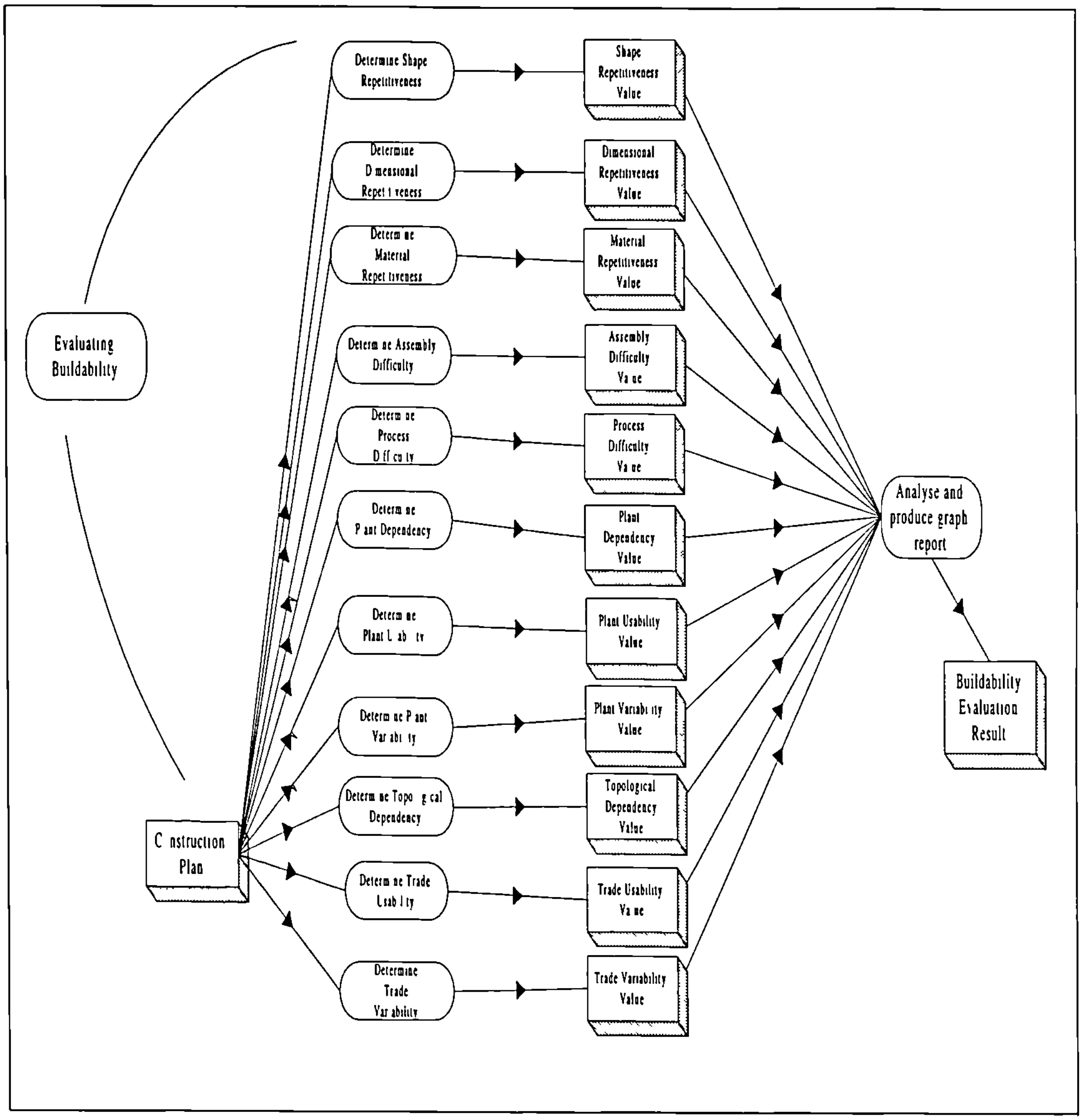


Figure 7.14 OFD for the 'Provide Buildability Evaluation' processes.

For example, the 'Determine Shape Repetitiveness' process produces 'Shape Repetitiveness Value' which indicates the percentage of elements with a certain shape over the population of that element type. The 'Determine Assembly Difficulty' process, however, produces the 'Assembly Difficulty Value' object that indicates the percentage scale of difficulty of an element being converted from the basic building material to form a final product. Both construction and design information are used to derive the value of the 'Assembly Difficulty Value'. The 'Determine Trade Usability' process. will produce the 'Trade Usability Value'. In this process, it indicates the scale of usability for the trades involved to realise an element.

When all the buildability criteria have been evaluated, the process 'Analyses and Produce Graph Reports' collates the values which are derived from the above processes to be presented in the buildability report. An object 'Buildability Evaluation Result' is produced which consists of line graph charts, text and graphical images of the facility.

7.6.4 The object relationship diagram for buildability evaluation

For the proposed buildability evaluation, Figure 7.15 illustrates its object relationship diagram. This is an extended ORD from Figure 7.13. In the diagram, the 'Building' object is evaluated by various criteria such as 'Aesthetic', 'Functional And Performance', 'Buildability', 'Cost' and 'Time'. Each of these criteria has a different approach for evaluation. For example

'Cost' and 'Time' can be projected from the construction plan and the estimating process. While 'Aesthetic' and the 'Functional and Performance' are evaluated by the designers. For 'Buildability' objects on the other hand, are evaluated by the 'Buildability Index' where it is determined by 'Repetitiveness', Functional Use', 'Location Factor', 'Trade Utilisation', 'Plant Utilisation', 'Facility Utilisation', 'Assembly', and 'Elements Dependency'. The object 'Repetitiveness' for example, is represented by several type of objects such as 'Material Used', 'Shape Applied', 'Specification Used' and 'Dimension Applied'. Each of these objects also carry different methods of assessment.

The 'Repetitiveness' refers to the frequency of objects like 'Material Used', 'Shape Applied', 'Specification Used' and 'Dimension Applied' appear in the design solution. For example, the 'Material Used' of an element represents the frequency of that material being used over the population of that element type in the project. The value of the 'Material Used' indicates whether it is a unique or common material. If it is a unique type of material, it imposes greater constraint on the operation on the site, since greater precautions have to be made in handling the material.

The object 'Functional Use' refers to the functional attribute of a building element which can be divided into several types of objects such as 'Architectural Requirement', 'Service Requirement' and ' Structural Requirement'. Each of these different objects have special impact on buildability evaluation. The object 'Location Factor' describes the position of the building elements within the project. All the analysis information used for the objects 'Repetitiveness', 'Functional Use' and 'Location Factor' can be derived from the design specifications.

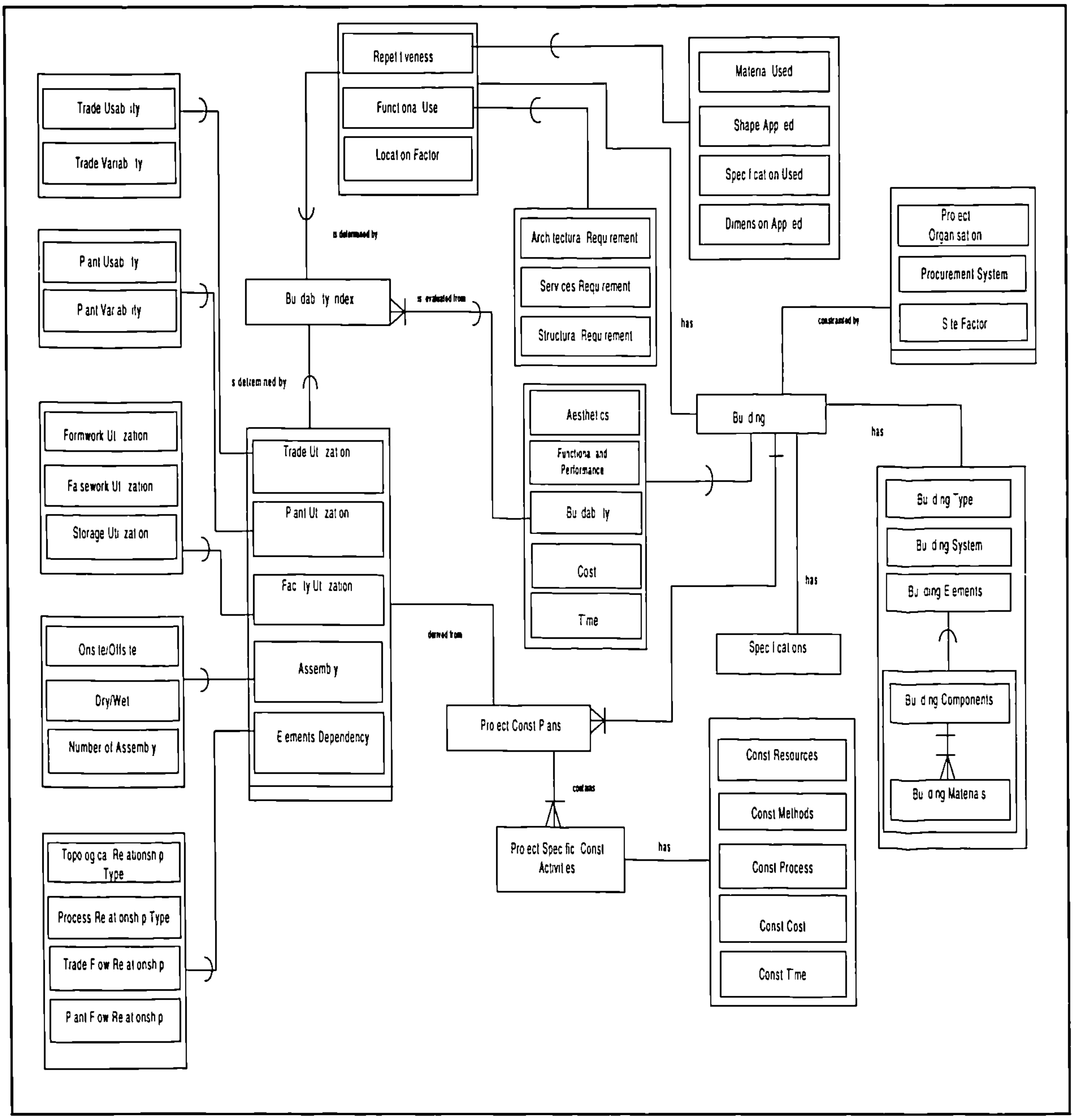


Figure 7.15 Object Relationship Diagram for Buildability Evaluation.

The 'Trade Utilisation' object is represented by 'Trade Usability' and 'Trade Variability'. Both of these objects supply the value for 'Trade Utilisation' evaluation object. The 'Trade Usability' evaluation object identifies the number of various trades required to realise an element, while 'Trade Variability' evaluation object dictates the inconsistency in the use of the trades. The same principle is also applied to the 'Plant Utilisation' which has two evaluation elements, namely 'Plant Usability' and 'Plant Variability'.

The object 'Facility Utilisation' highlights the facility that is used to construct an element. To represent the various facilities which have been used by an element and their impact on the design, the 'Formwork Utilisation', 'Falsework Utilisation' and 'Storage Utilisation' are defined to be part of the 'Facility Utilisation' object. The object 'Formwork Utilisation' refers to the frequent use of a selected type of formwork to construct an element from various other types of formwork in the project. The value obtained from 'Formwork Utilisation' highlights whether the formwork is fully utilised for the project. A similar principle also applies to the 'Falsework Utilisation'. The 'Storage Utilisation' object describes the space occupied by the formwork or falsework on the site. The value of this object indicates the importance of the space with the required facilities.

For 'Assembly', the object is represented by three types of evaluation elements namely the 'Onsite/Offsite', 'Dry/Wet' and 'Number of Assembly'.

'Onsite/ Offsite' object indicates whether any of the construction methods used to realise the element is done on site or elsewhere. 'Dry/Wet' object represents whether the construction process is dry process or wet process. The object 'Number of Assembly' represents the number of different construction activities required to construct the element.

The 'Elements Dependency' refers to the various types of construction relationships that might effect a building element during its construction. These types of relationships are 'Topological Relationship Type', 'Process Relationship Type', 'Trade Flow Relationship' and 'Plant Flow Relationship'. 'Topological Relationship Type' of an element is based on the structural or physical relationship of an element with others e.g. supported by relationships can be defined between beams and columns. The type of relationship between the building elements state the degree of importance on the relationship. Since a building element can have one or many relationship with other elements, the number and the type of relationship will indicate the importance of a building element with its associated element.

'Process Relationship Type' is concerned with the relationship of various wet or dry production methods. For example, when constructing a reinforced concrete column, several 'dry processes' exist such as placing reinforcement, erect formwork, etc. and other 'wet processes' such as mix concrete, place concrete, etc. These different processes imposed various managerial and technological constraints on the production process.

The 'Trade Flow Relationship' refers to the involved trades when constructing an element. The flow and the utilisation of the trade from one process to another dictates the value of the 'Trade Flow Relationship'. If many and different trades are required to realise an element, it indicates the complexity of the production process. The 'Plant Flow Relationship' also uses similar evaluation concepts with the 'Trade Flow Relationship'. For objects such as 'Trade Utilisation', 'Plant Utilisation', 'Facility Utilisation', 'Assembly Buildability' and 'Buildability Elements Dependency', the basic information for supporting the assessment is derived from the 'Project Const Plans'.

The 'Project Const Plans' object provides construction information for the majority of the above objects. It has a one or many relationship with the 'Project Specific Const Activities'. For each of the 'Project Specific Const Activities' it contains the 'Const Resources', the applied 'Const Methods', the 'Const Process', the 'Const Cost' and the project 'Const Time'. The values of these objects determine the basic construction information of the 'Project Specific Const Activities'.

7.7 Summary

This chapter has reviewed the object oriented methodology and outlined Martin's object oriented techniques. Based on Martin' s techniques, several object relationship and object flow diagrams are presented to illustrate the construction planning and buildability information models. The succeeding chapter will outline SPACE (Simultaneous Prototyping for An Integrated Construction Environment) as an integrated platform. where the proposed information models are developed as part of the applications in the system.

Chapter 8
SPACE Construction Integrated Environment

8.1 Introduction

The lack of standards, the complexity and the large amount of information involved in the construction project, have made the tasks of developing computer integrated environments for co-ordinating and communicating information very difficult (Turk, 1994; Aouad *et al.*, 1993; Sanvindo, 1992; Watson & Crowley, 1994; Tah *et al.*. 1994; Alshawi & Faraj, 1996). Nevertheless, the need to establish a general framework of such a system has been a major aim for many research institutions. Various published reports such as Technology Foresight (Progress Through Partnership. Part2 1995), Building IT 2000, etc., have addressed this issue and highlighted it as a major concern for future practices in construction. If the integrated system can be effectively implemented to support the whole life cycle of project, significant improvements could be gained by the industry.

This chapter presents an integration approach which supports multiple construction applications in a computer integrated environment. This approach has been implemented in an integrated environment SPACE (Simultaneous Prototyping for An Integrated Construction Environment) which was developed with the aim of co-ordinating the integration process between the various construction applications. The prototype has been developed by the AIC (Automation and Integration in Construction) research group at the University of Salford.

8.2 The Integrated Construction Environment (ICE)

The lack of a high level structure for an integration environment of a computer system for construction, has led to the development of a series of small isolated integrated applications in various fields of construction. Unfortunately, this isolated development of computer application has created many disadvantages to the user. Yamazaki (1993 & 1994) has identified major problems with the current system which are;

- the system could not adjust to the business need when change is required.
- basic information and knowledge of construction could not be shared amongst the project participants.
- interactive procedures where design or construction solutions can be evaluated at an early stage have not yet been developed.
- systematic evaluation and feed back for various participants are not available.

The AIC research group has proposed a modularised product model for an Integrated Construction Environment (ICE) from which all integrated applications can access their relevant information. The combination of the product and process models, which represent different applications, are put together to form what is known as a project model (Froese, 1995). The framework allows greater sharing of information between project participants, therefore providing a flexible interaction between the various data models, i.e. the project model acts as a central core for data sharing and exchange between various construction applications.

The conceptual structure of the proposed ICE framework is shown in Figure 8.1. It consists of three main parts i.e. the project model, software packages including interfaces with the project model, and external data bases. A modularised approach has been adopted in the development of the project model where each stage of the project's life cycle is represented by a module. These modules are supported by process model /methods/events which are necessary to describe the modules' behaviour and relationships with each other and with the external world i.e. application software packages and external databases. Moreover, each module is supported by a knowledge base which adds intelligence to its behaviour.

8.2.1 The project model

The project model comprises a building data module and other application data and process modules. The building data module mainly describes the building's elements and their attributes. The extent and structure of this module depend on the scope, the context, and the main objectives of the ICE e.g., an environment for concrete framed buildings may have a different structure to that of steel. Other application data modules, on the other hand, represent data required by other stages of the building's life cycle such as specifications, estimating, construction planning, site layout planning, etc.

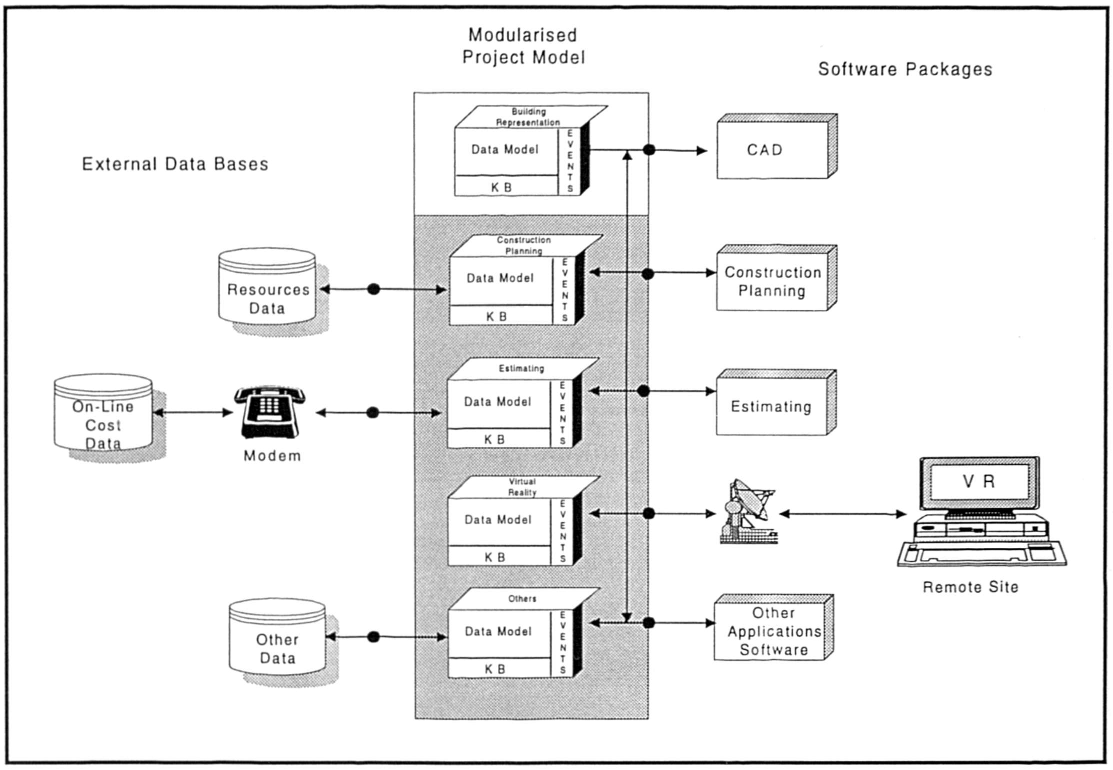


Figure 8.1 Proposed framework for the integrated construction environment (ICE)

Each of these modules must be developed to fulfil the need of a particular construction application. For example, a construction planning application requires an application data module to support the information required by the planning process e.g. generic construction activities, resources available, construction methods, etc. The modules are designed to complement each other and to maintain and share data in the most efficient way. In this approach, data related to a particular stage of the project's life cycle is maintained separately form other data, but makes use of other modules' data as and when required. For, example a construction planning data module contains generic information about construction activities, methods, resources, etc. When it is activated, it refers to the building data module, where information about the current project is stored, to generate the project's specific construction activities.

These data models are static representations of data i.e. they do not interact with each other. Interactions between the various data models are carried out and controlled by the applications. This means that if an application needs specific information from another data model than that of its own, it activates a function within its own data model which sends a message to the relevant data model asking for the required information. This approach can significantly control the development of the ICE and create an excellent maintenance strategy for the whole environment.

8.2.2 Software packages and external databases

The second part of the ICE represents the construction applications packages such as CAD, construction planning, estimating, virtual reality, etc. Such application software packages can either be external, i.e. stand alone applications packages, or internal i.e. developed within the environment of the ICE. In either case each application has 1) its own user interface to manipulate the information, and 2) a specially developed two way communication channel to transfer information between the application and its related application data module at real time, Figure 8.1 (the interfaces are represented by dots on the communication line). These application packages are completely independent from the project model.

The third part of the ICE environment is the external databases. The project model can retrieve external information from external databases as and when required by the various involved modules. This process can be carried out directly by the involved module or shared by a number of application modules e.g. estimating and construction planning applications may need to share the cost data which can be retrieved by any of these applications say from on-line database.

8.3 The multiple views provider

The proposed concept of the objects' life cycle, within the modularised project model in the ICE, provides an excellent tool to satisfy the widely debated issue of providing multiple views. Once an object is instantiated and entered the third phase of its life cycle, it can respond to different application data modules according to their needs and requirements. The application data modules, from the users point of view, can illustrate the realisation cycle of a construction process such as design, tendering, construction, refurbishment, etc. (as previously explained). Each of these stages refers to a particular application data module which is in turn a speciality domain of a particular profession (user). Therefore, each application data module can be considered as a view i.e. a view is equivalent to an application data module. Views can be as complex and detailed as those corresponding application data modules (Alshawi, 1995). Figure 8.2, illustrates this principle.

To illustrate this concept, lets consider a "column" object. If this object exists in the BDM and the integrated environment is supported by three application data modules such as structural design, construction planning, and estimating, then the object can provide three views which correspond to these application data modules. If a structural design package accesses the structural data module with the aim of designing the object "column" then the structural data module interrogates the object "column" for specific information and then displays or sends this information to the structural design package. On the other hand, if a construction planning package accesses the construction planning data module requesting specific construction activities which are required to construct the object "column", the "column" object responds to this application data module by sending its milestone construction activities. The construction planning data module then processes this information and displays or sends them to the planning package.

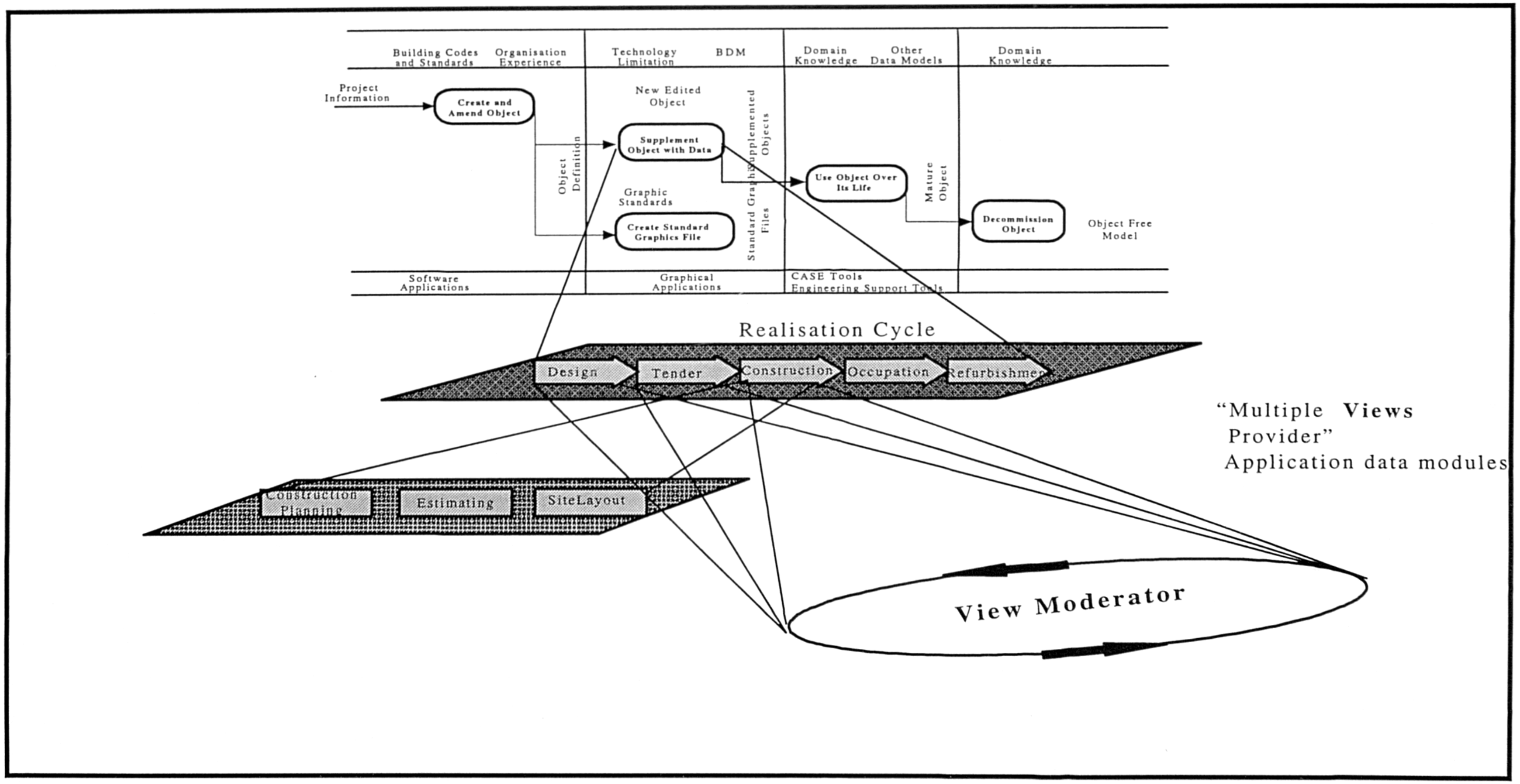


Figure 8.2 The concept of providing multiple views

However, for some views it may not be possible to extract all the information required from one single application data module. For example, if a cost estimate is required for the object "column", the cost will depend on the construction planning data module as well as the specification data module. Thus, to provide the cost's view to users, the estimating data module requests specification from the object "column". The objects "column" points to the specification data module where its specification is extracted and sent to the estimating module.

This information is then shared between the estimating data module and the construction planning data module. The latter uses this information to decide on the best construction method required to construct the column and then allocate the required resources. All this information is then given to the estimating data module to provide the required cost estimate.

This process requires a structured procedure in order to carry it out effectively and efficiently. "View Moderators" have been introduced for this purpose. These moderators are defined as a dynamic collection of methods which are required to satisfy a particular view within an application data module. However, their existence and complexity depends on the status of the environment when the view is requested. In the above example, if the specification of the object "column" has not yet been generated, the cost estimate's view moderator asks the object to generate its specification. If the specification has already been generated then the view moderator will directly access such information. View moderators are normally stored in the concerned application data modules and are triggered off by the application packages.

8.4 Implementation

The conceptual structure of the proposed ICE has been implemented in a PC based environment SPACE (Simultaneous Prototyping for An Integrated Construction Environment). Its constituted of CONPLAN and five other main modules, these are described below;

8.4.1 *CAPE* (Construction Application Protocols For ComprEhensive data Transfer)

The aim of CAPE (Che Wan Putra, 1997) is to establish, generate, control and store comprehensive project specific information, representing the generic multiple designers' views of a building model for reinforced concrete office buildings. The information produced by CAPE includes most of the physical building information such as project specific information and details of building elements, i.e. geometry, topological, location, etc.

CAPE controls the flow of information between AutoCAD^{TM} (as the design tool) and the central core (Alshawi & Che Wan Putra, 1995). This model acts as the main distributor of project's specific information to the other data models.

8.4.2 *SPECIFICATION*

SPECIFICATION (Underwood & Alshawi, 1996) module produces the specification of each of the building elements which are retrieved from databases of standard components/materials. These databases have been developed based on WESSEX's cost database. The specification describes the building element component such as brick or concrete, inner or outer wall, insulation type, mortar mixes, etc. Each specification is only created once in the *SPECIFICATION*'s module, which is later referred to by other building elements.

8.4.3 *CONVERT* (CONstruction Virtual EnviRonmenT)

The aims of *CONVERT* (Alshawi & Faraj, 1995) is to support the applications that perform functions within the project life cycle by mapping the views of these applications to the virtual environment. The application generates virtual reality models for the design elements created by AutoCAD/AEC^{TM} at real time. *CONVERT* also enables the virtual objects to be interrogated.

8.4.4 *INTESITE* (INTElligent SITE Layout Planning)

INTESITE (Alshawi & Sulaiman, 1995) aims is to provide the site specific layout information, i.e. the arrangement of temporary facilities for the selected resources from project construction planning and design information. The site geometry is created using AutoCAD™ and transferred into the project model. A site planning model represents the know-how for positioning the construction resources on site as and when required by the construction activities.

8.4.5 *EVALUATOR* (Project Estimate and Interim VALUation GenerATiOn in an IntegRated Environment)

The main purposes of *EVALUATOR* (Underwood & Alshawi, 1996) are to produce project estimates in the form of elemental BQ and to generate monthly interim valuation certificates from the construction plan. An estimating model which represents the product and process models for project estimating and monthly interim evaluation were produced.

The information from these models is utilised through the central core to generate the basic estimating data and conduct the monthly interim evaluation of the project. *EVALUATOR* utilises virtual reality as an interfacing tool to simulate the project based on the valuation period.

8.4.6 *CONPLAN* (intelligent CONstruction PLANning for design rationalisation)

The main purposes of CONPLAN are to develop a project specific construction plan and buildability evaluation of a design. Detail explanations of CONPLAN are described in Chapter 9.

At its current stage of development, SPACE integrates four external and one internal application with central data models. The external applications are; design, construction planning, virtual reality modelling and site layout planning, while the internal application is cost estimating. These applications have been implemented using commercial software i.e. AutoCAD™ for the design and site layout planning, CA-Super Project™ for the construction planning application, and World Tool Kit™ for the virtual reality application. KAPPA-PC™ has been used as the information engineering support tool where all the data models are implemented. Moreover, the Cost estimating application has used KAPPA-PC™ as its implementation media.

8.5 Summary

This chapter has described SPACE as a computer integrated environment, and outlined its approach, its system architecture and its application modules. The following chapter will outline the aims of CONPLAN as a prototype integrated system, it implementation process, its system architecture and its development as part of SPACE module. The chapter will also highlight the interactions and functions of CONPLAN to support other applications in the system.

Chapter 9
CONPLAN: The System Architecture, Implementation And Application

9.1 Introduction

The information models in chapter 7 have highlighted the various types of information and processes required to develop the construction plan and perform buildability evaluations within an Integrated Construction Environment. Chapter 8 described the integrated framework and the approach used by CONPLAN to establish the Integrated Construction Environment (ICE) system. In this chapter the system architecture, system development and the application of CONPLAN (Intelligent CONstruction PLANning for Design Rationalisation) are described. The system architecture describes an overview of CONPLAN as an integrated system. The system implementation describes the processes of developing the system components which involve knowledge structure, representation and processing while the system application in CONPLAN outlines various steps and methods used to represent and implement the problem domain in the system.

9.2 The system architecture

The main aim of the CONPLAN module is to provide a construction plan and utilise the information contained in the plan to produce the buildability analysis for a design solution from construction perspectives. The CONPLAN architecture consists of external applications and a central knowledge based system. The application specifics used by CONPLAN are the graphical interfaces, a project management system and databases. Each of these application specifics provides various important functions for CONPLAN. The graphical interfaces act as an input to capture the information of design into a building product model which is developed by CAPE (CheWanPutra, 1997) and also provides output for CONPLAN as visualisation tools to highlight buildability analysis results and construction simulations. The project management software is used as a tool to display the construction plan in either format CPM network or Bar chart. It also provides time and cost related information back to the central knowledge base. The databases are utilised by CONPLAN as an input for resources data.

The central knowledge base system contains the various data models and procedural knowledge required to accomplish CONPLAN's main aims. It contains the design information, construction knowledge, and the various processes which are required for generating the construction plan, and buildability evaluation. The knowledge based system controls the system's input and output, the user interfaces and the project management system tool. Figure 9.1 depicts the system architecture of CONPLAN.

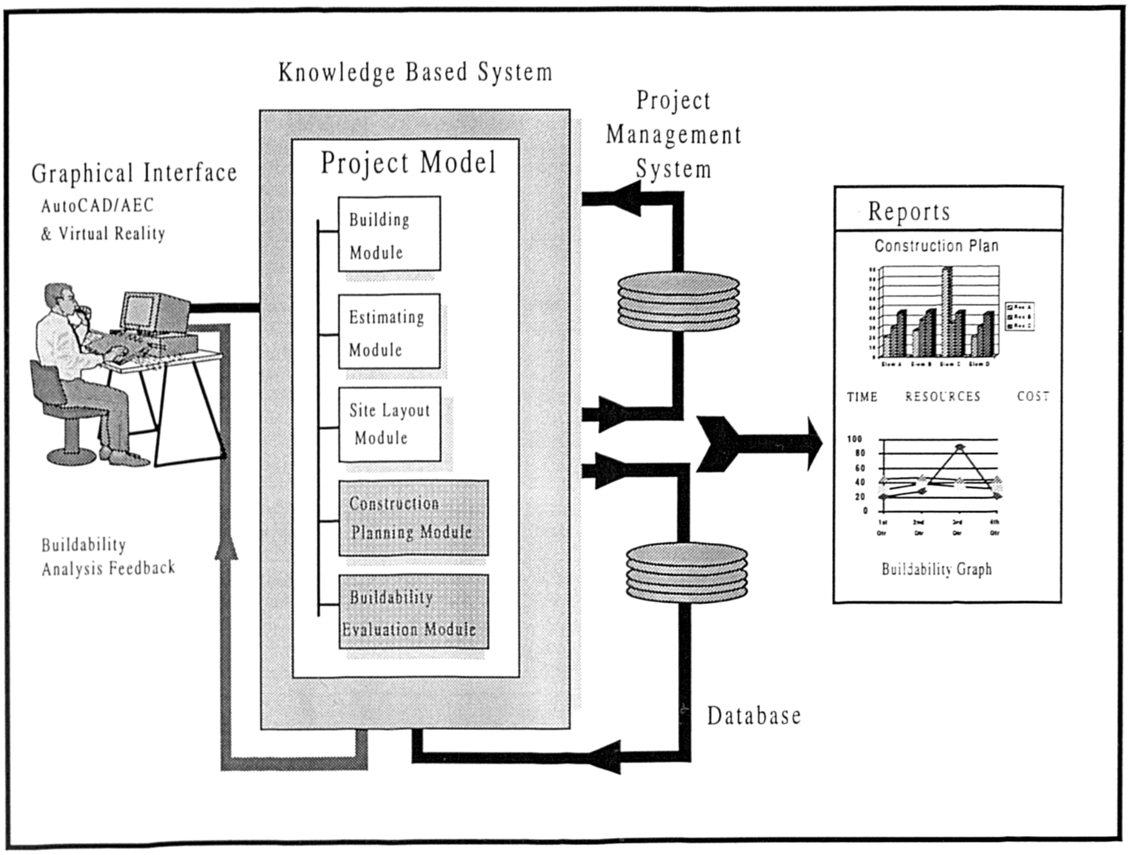


Figure 9.1: CONPLAN system architecture.

9.2.1 The system input

The input required by CONPLAN is divided into three parts; the information about the design, the construction resources data and feedback information from the project management system. The design data is obtained through a graphical interface (AutoCAD™ /AEC™) which is interpreted by CAPE

(CheWanPutra, 1997) to form an object oriented building elements specific information.

The resources data on the other hand, contains data regarding productivity output, cost per day, availability of plant, etc., which is obtained from external databases. Several flat file structures have been constructed for this purpose.

The third input required by CONPLAN is the feedback information regarding the project specific construction activities which are obtained from a project management system such as duration, construction cost, date start and finish, etc. This information however, is only available after CONPLAN has initially generated the construction plan.

9.2.2 The knowledge based of CONPLAN

The CONPLAN knowledge based system consists of three main processes, namely collating design information and relevant construction methods, develop construction plans, and performs buildability evaluations on the design solution (Figure 9.2). Each of these main processes perform their operations through various functions and methods developed within the knowledge based system.

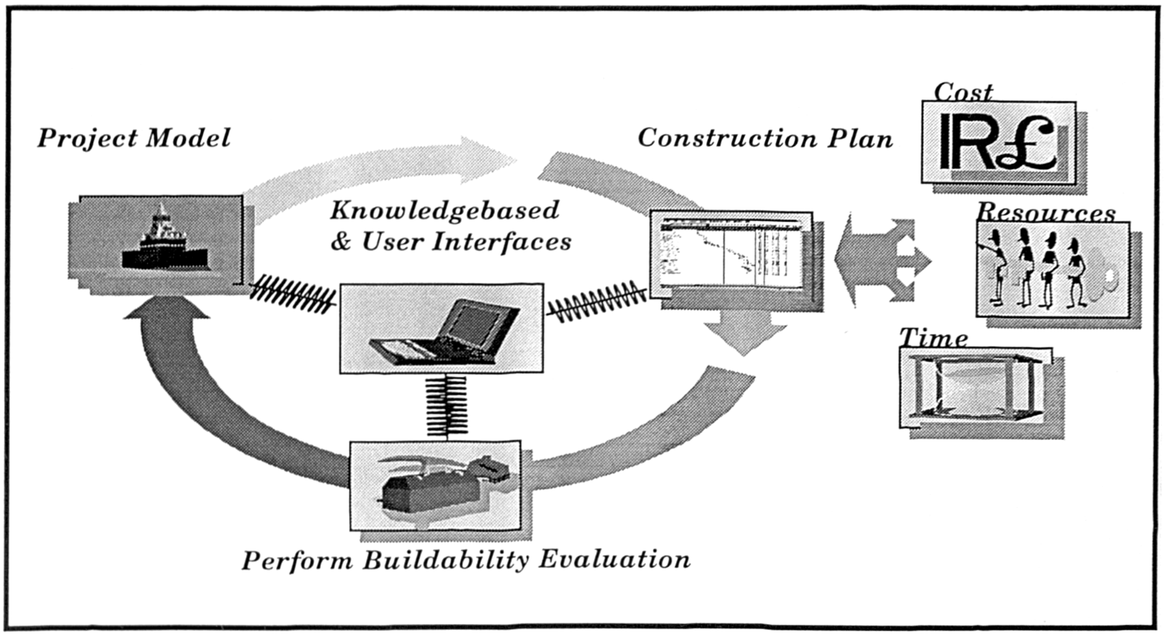


Figure 9.2: The main processes of CONPLAN.

a) Collating the design and construction resources information

The collating of design information and construction resources in CONPLAN is executed through the design and specification (Building Module) and the selected construction method and resources database (External databases) (Figure 9.3). To generate the plan, firstly CONPLAN identifies the type and attributes of the building elements. For example, CONPLAN sends a request to an estimating module to invoke the various quantity calculation functions to obtain all the building element quantities. These attributes values will determine the workload and types of construction activities required for the construction plan. While the design and specification (Building Module) provides the information for CONPLAN to decide what to be constructed, the resources data provides CONPLAN with the information on how it can be constructed. A method of construction has to be decided for each of the construction activities from the available construction resources. Since, this selection process required multiple views (i.e. estimating, plant management, site layout planning manager, material management, construction planner, etc.), it is assumed that the list of the selected construction methods available for CONPLAN have already been decided initially by the construction participants which is stored in the databases.

For examples, lifting concrete by crane and skip, mixing concrete using site mixer, etc. The specific construction resources i.e. type of crane, in the construction methods will be selected by CONPLAN or the user later in the process for each of the construction activities. The collation of these resources for the construction activity in CONPLAN is done through a knowledge processing which captures the appropriate type of resources from a database and stores it in the knowledge base structure. The cost and the productivity output of the construction method will be referred to by CONPLAN to calculate the duration and cost of construction. The selection and availability of these resources would influence the outcome of the overall project construction plan which will later be used for buildability evaluation. Figure 9.3 shows the general functions involved in CONPLAN for generating the construction plan and buildability evaluation.

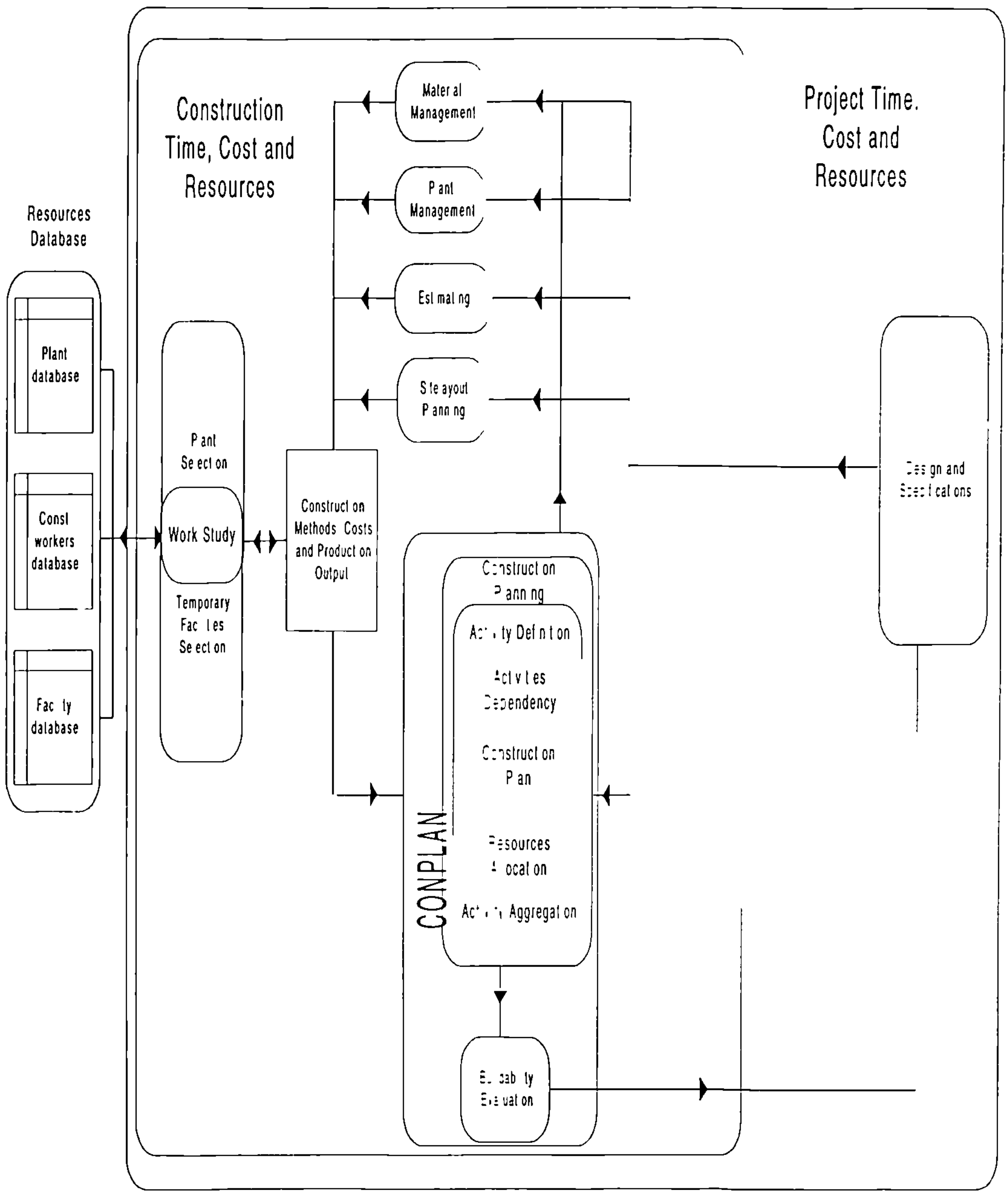


Figure 9.3 Conceptual process structure involved in CONPLAN.

b) Develop construction plan

By using the collated information described earlier, CONPLAN has adopted a middle-down-and-bottom up approach to generate the construction plan in the project management system. Figure 9.4 demonstrates how this approach works and how different levels of construction details can be obtained.

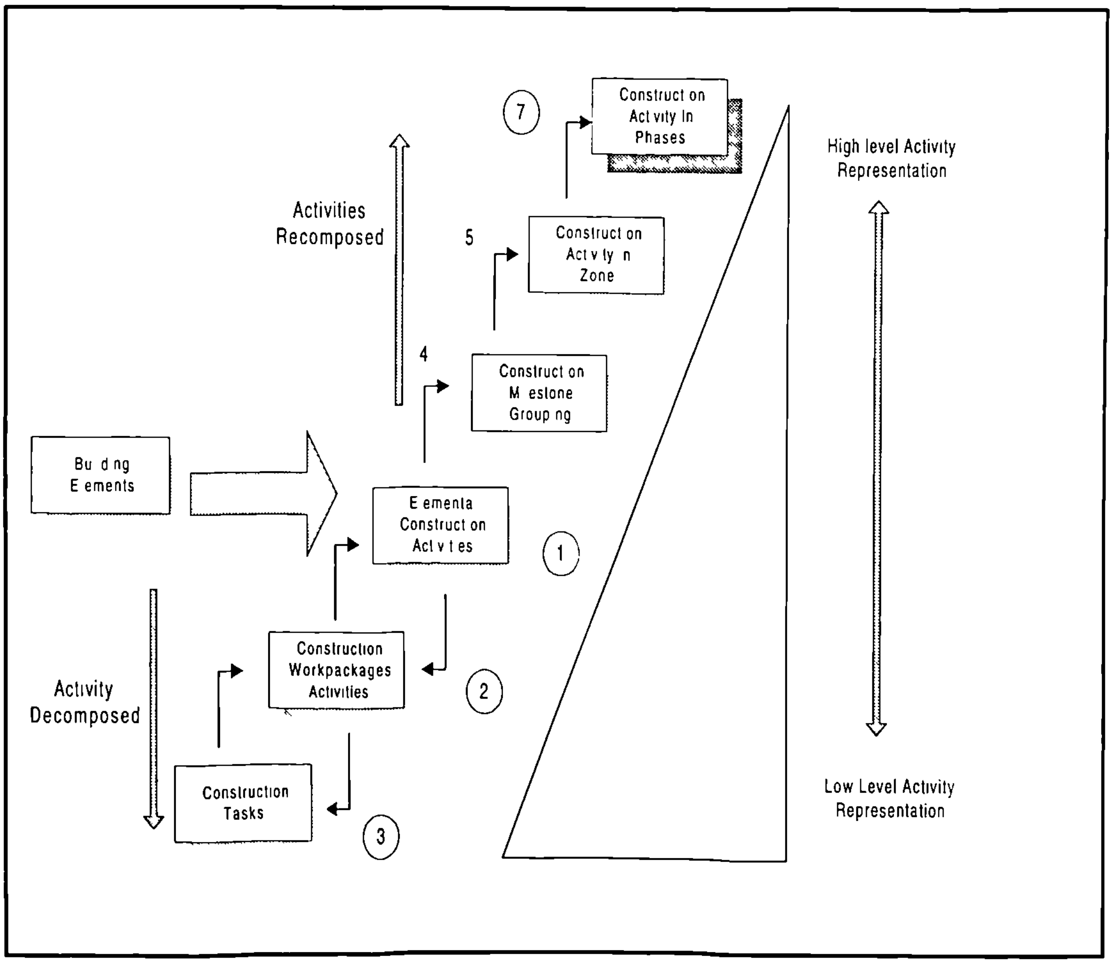


Figure 9.4: Middle-down-and-up approach of CONPLAN.

The following points briefly explain such an approach:

1. Design elements are first converted into elemental construction activities.

2. The activities produced in (1) above are decomposed into their constituents, whereby the work packages which are required to carry out these activities are further determined. For example, the elemental construction activity Construct Ground Beam-1 can be decomposed into Excavate Ground Beam-1, Form work Ground Beam-1, Reinforcement Ground Beam-1 and Concreting Ground Beam-1. The identification of the construction tasks (2) are then determined including their required resources, duration, and dependency.

3. Once the construction tasks (3) and its resources are determined and since these activities are the sub activity of the higher composition representation, the established duration and cost obtained from this level is incrementally aggregated upwards to represent the higher level of construction activities i.e. to workpackages, elemental, milestone, zone, phases etc.

4. Milestones, zones and construction phases (4, 5 & 7) are then determined according to the available resources simply by continuing the previous aggregation upwards.

c) Perform buildability evaluation on the design

Once the construction plan is produced, the next function of CONPLAN is to perform the buildability evaluation on the design solution. For this process, three main tasks are performed by CONPLAN, namely retrieving construction information from the project management system, producing and evaluating the buildability data, and displaying analysis results. Using this data, CONPLAN performs the various processes of buildability evaluation on the design solution where some extra information is required from the user when this evaluation is performed (this is explained in 9.6.3).

9.2.3 Output of the system

CONPLAN produces three types of output: the project specific construction plan which is displayed in the project management software, the project construction simulation in virtual reality and a report of buildability evaluation using a line graph, textural information and virtual reality representation. The graphical interface used in CONPLAN mainly aims to provide the user with a visualisation facility for the construction simulation and the result of a buildability evaluation when it is completed. While the line graph and textural information summarises the results obtained from the various elements of the buildability evaluation. The generated construction plan is also used as an input for other applications such as estimating, site layout planning, buildability evaluation, etc.

9.3 The system environment

As explained in Chapter 8, CONPLAN is part of an integrated construction environment (ICE) "SPACE". Other applications which have been developed in this environment are design, estimating and site layout planning. CONPLAN uses most of the environments facilities. Among these facilities are:-

- The graphical interfaces: SPACE graphical interfaces are used to enable designers to create and visualise the design solution. AutoCAD™/AEC™ is used to present and enter 2D information while World Tool Kits™ is used for virtual presentation of the design objects. Both tools are used by CONPLAN to obtain design data as well as projecting the outcome of the system. CAD functions are oriented towards the creation, modification and deletion of graphic elements or primitives, and the transformations of these elements and combinations of them in two and three dimensions. Since AutoCAD™/AEC™ is only capable of producing primitives output of design data, CAPE (CheWanPutra, 1997) captures and interprets this data into a meaningful class of objects and presents them in the building module. The World

Tool Kits™ on other hand, which is used by CONPLAN to project the construction simulation and buildability evaluation, is a virtual reality tool that has been customised by CONVERT (Alshawi & Faraj. 1995). Both graphical systems run on Window 95™ and Window 3.11™.

- The knowledge base system: The CONPLAN knowledge-based system is implemented in KAPPA-PC™. The software is an object oriented knowledge-base environment which has facilities such as forward and backward chaining, explanations, on-line knowledge base editor, inference tracing, user interface representations, object browser, etc. The KAL interpreter language provided in the software, enables users to write and test programs. The software runs on Windows environments and supports dynamic data exchange (DDE) and SQL for databases. The GUI builder provided in the application has various Active Images package such as bitmaps, button, line plot, slider, etc.

- The project management system: This is a project management software which is normally used for planning (activities, cost, resources) in a project management function. Besides providing the algorithm for creating project network activities, the application has various functions for budgeting, cost control, project control, etc. Since the CONPLAN function is to create the construction activity network, the project management software CA-SUPER PROJECT™ is used for this task. The software has all the facilities for project management such as Project

Evaluation Review Technique (PERT), Critical Path Method (CPM), bar chart, scheduling, resources levelling, costing, etc. Besides, the import and export file formats facility, the software is also equipped with an advance data transfer i.e. dynamic data exchange (DDE). CONPLAN uses these facilities and its commands to control and communicate to and from this software. For example DDE is used to create the construction activities, its resources, its dependencies, calculate the plan duration and cost, develop a project plan presentation, and retrieving the formulated data.

- Database system: This software is used by CONPLAN to store resources data. Since there are numerous type of resources required for construction i.e. plant, labours, temporary facilities, etc., the use of this software in CONPLAN facilitates data management for the resources. CONPLAN uses DBASE™ to store this resource data. The extraction of the resources data is controlled from knowledge based systems through KAL commands of SQL (Standard Query Language).

9.4 The system implementation

The implementation of CONPLAN is based on the schema of object oriented frame-based knowledge representation. The method of representations available in the development tool (KAPPA-PC™) such as object hierarchy, attributes, inheritance, associations, methods, encapsulation, etc. supports the system implementation requirements for the domain models.

The knowledge structure of CONPLAN i.e. its object's representations and behaviour which have been established using the object oriented modelling technique, were implemented in the development environment. Unlike the traditional information modelling techniques, all the objects in the information models (object relationship diagrams and object behaviour diagrams) are capable of being directly implemented in the object oriented knowledge base development environment. Nevertheless, the implementation system for CONPLAN is established through the knowledge structure, knowledge representation and knowledege processing.

9.4.1 Knowledge structure

The scope of the knowledge structure representing the construction planning and buildability evaluation is only limited to the production of the initial construction plan while for buildability evaluation, it uses construction information from the construction plan and general buildability principles. CONPLAN knowledge structures are represented and developed as part of the SPACE project data model. The knowledge structures are directly implemented from the various objects defined in object flow and object structure diagrams (Chapter 7) which are formed into object classes, hierarchies, attributes, methods and functions .

There are four main independent knowledge structures which are required for CONPLAN's implementation; the building elements hierarchy, the construction activities hierarchy, construction resources hierarchy, construction plan hierarchy, and buildability which is represented in each of the building element instances as evaluation attributes. Other knowledge structures which assist CONPLAN's operations are the estimating and site layout. Figure 9.5 illustrates the knowledge structure of CONPLAN in an integrated construction environment.

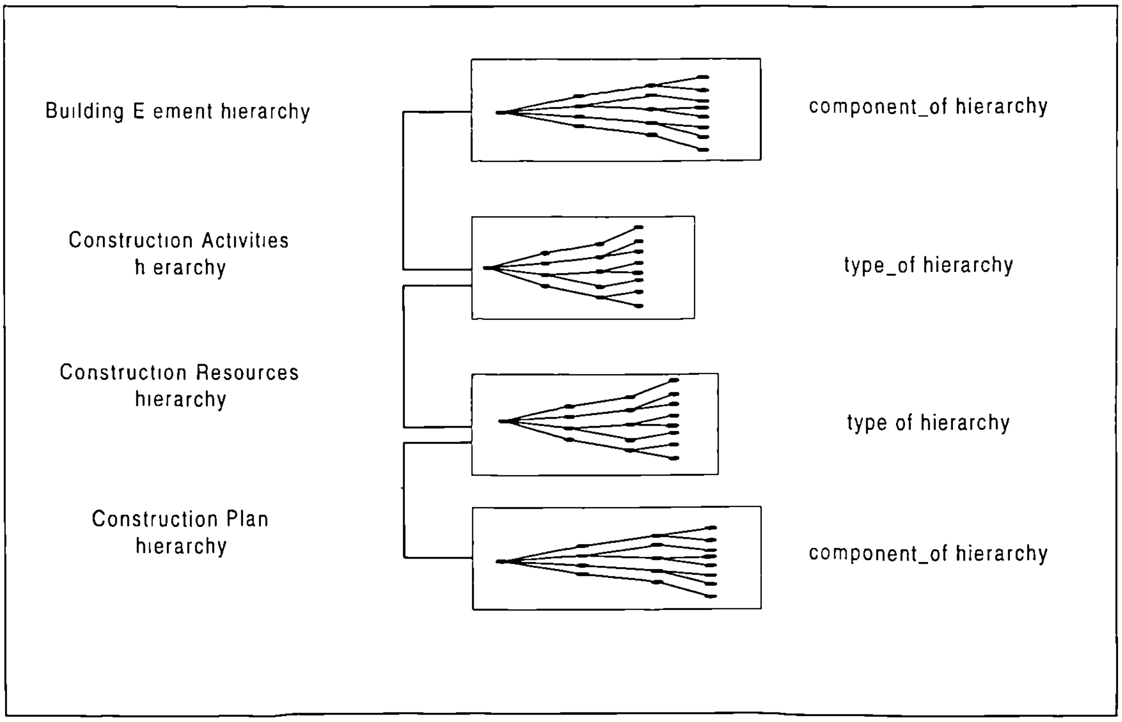


Figure 9.5 The various knowledge structures used by CONPLAN

Since in construction, a building is built component by component, a building elements knowledge structure, which describes the type of and the composition of elements in a part_of hierarchy, for a specific building model is essential for CONPLAN. This knowledge structure facilitates CONPLAN to use the high level building description and its parts to identify and allocate the appropriate construction activity to the building elements based on its physical properties, its components, its material and its specifications. It also enables CONPLAN to perform buildability evaluations for each of the building element instances.

To perform the construction planning processes, three types of object class structures are required, i.e. the construction project plans, construction activities and construction resources. The construction project plans structure represents the level of detail of the construction plans. The creation of the representations from this knowledge structure depends on the size of the project, availability of construction resources and the user requirement. The construction activities knowledge structure is represented by a type_of hierarchy.

This hierarchy represents the generalisation/specification of the construction activities normally established for construction of a reinforced concrete facility. The construction resources structure however depicts the type_of hierarchy of construction resources. The resources are divided into three types i.e. labour, plant and temporary facilities.

For describing the various components of the construction plan, its knowledge structure is established by using components_of hierarchy. The structure of the hierarchy will allow the construction activities representation in the construction plan to be aggregated according to various levels of abstraction. It also allows the construction activities to be allocated with correct construction methods, resources and calculation for duration, and cost for the construction plan.

Before CONPLAN can be operated, an instantiation of a building model is required. The instantiated building model will form the specific information of the project. To generate the construction plan and the buildability analysis for the building model, the knowledge structure in CONPLAN will create additional attributes and values in the instantiated building model. It will also use the generic knowledge structure of the construction activities and resources to instantiate the required construction planning information to form a plan. These instantiated construction activities and resources will become the project specific construction activities. With these new instances, attributes and values available in the various knowledge structures, CONPLAN will be able to develop the construction plan and the buildability analysis.

9.4.2 Knowledge representation

Each hierarchical class of objects in CONPLAN contains various attributes which describe specifically the static and dynamic properties of these objects. This hierarchy allows the knowledge in a parent object (super class) inherited by a child object (subclass) or the instances of that class objects. There are nine kinds of class objects used by CONPLAN. Seven of them do not have instance objects in the earlier stage. These are the Building Elements, Const. Activities,. Project Const. Plans, Const. Elemental Plan, Const. Milestone Plan, Const. Zones Plan and Const. Phases Plan.

For these seven class objects, an instance object which are project specific, will be created to present the project, depending on the size and resource availability of the project. The remaining two class objects are Const Resources and Const Options. They have instance objects, which are non project specific and serve as databases to provide the alternatives from which the user can select. Figure 9.6 illustrates the hierarchical object classes used by CONPLAN. The Building Elements object refers to the various elements of a concrete building. The Const. Activities objects are established based on the various types and components of generic construction activities. The Const. Methods objects however, define the various types of resources used specifically for executing any of the construction activity objects. The Const.

Methods used in the construction activities are selected from various Const. Options.

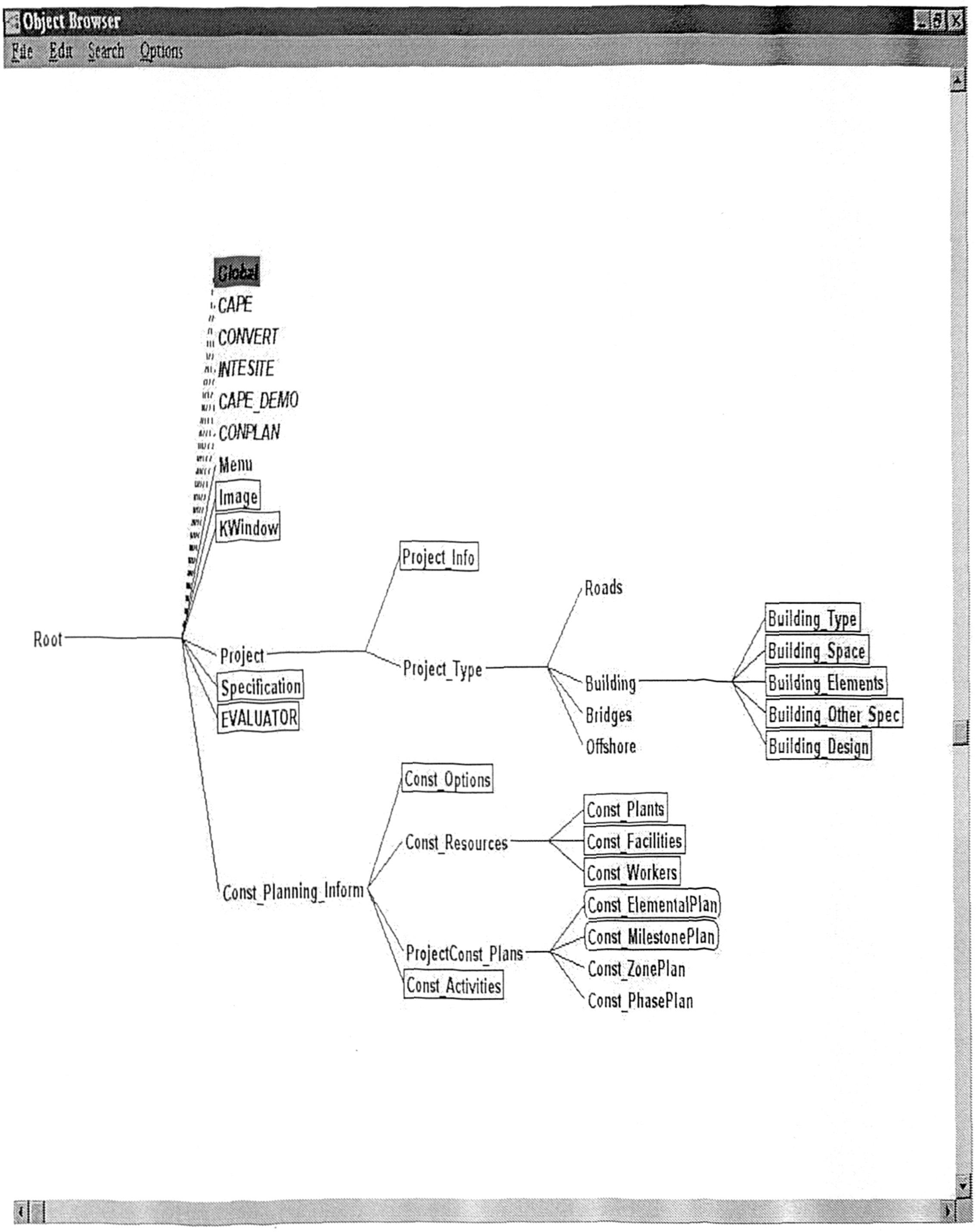


Figure 9.6 The object classes heirarchy used by CONPLAN

The Const. Resources however, describes the type of resources used in the Const Methods. Once the required construction activities are defined for each building's element object, its composition activities are instantiated accordingly to the Project Const Plans hierarchy. These composition activities would be outlined according to its levels of construction activity such as Const Tasks Plan, Const WorkPackages Plan, Const Elemental Plan, Const Milestone Plan, Const Zones Plan and Const Phases Plan.

a) The building elements

The Building Elements object hierarchy used by CONPLAN is developed by CAPE (CheWanPutra, 1997). Figure 9.7 illustrates the building element hierarchy representation. It consists of various types of elements such as Beam, Slab, Column, Wall, etc. Each object class in this hierarchy contains various attributes which describe uniquely the properties of the building element object. Among these attributes which CONPLAN uses are Is_A, Shape, Height, Width, Breadth, Location, Storey, Co_Ordination, Supported By, Attached_To, Associated_Elements and Element_Spec_Ref. Each of these attributes has a different contribution to the development of the construction.

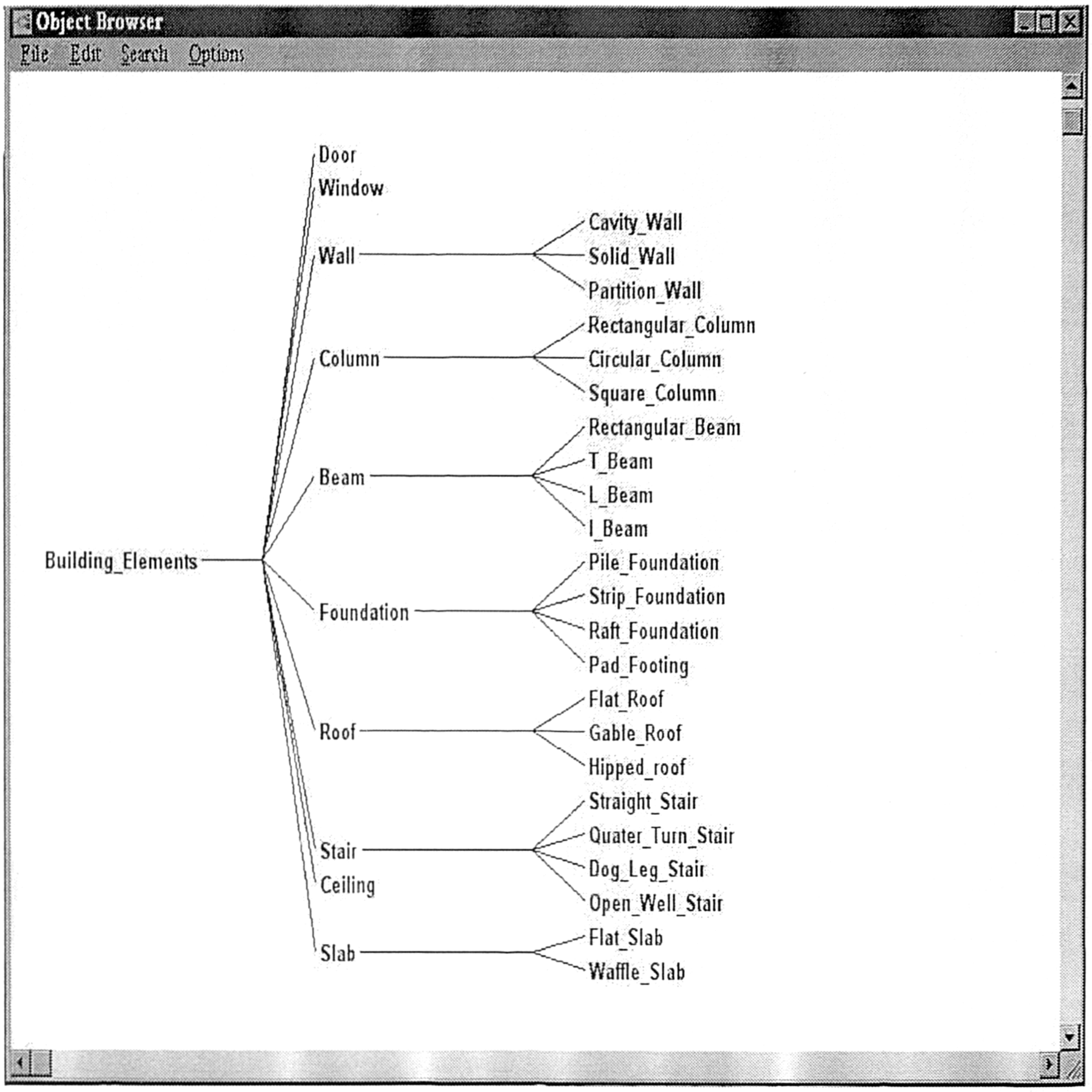


Figure 9.7 The building element hierarchy (CAPE, CheWanPutra, 1997).

For example, Is_A attribute value is used to decide what type of building element does the object specifically represent. While the value of the Supported_By or Attached_By attribute is used to establish the element's construction activity predecessor in the construction process. To decide the type of construction activities for the building element, however, the specification of the object which is described by the Element_Spec_Ref attribute is accessed.

The volume of work for a construction activity is established by referring to the geometrical values of the building elements object such as Height, Width and Length. In order to determine whether any type of mechanical assistant would be required for the established construction activities of the building element, CONPLAN will refer to the attributes value of Location, Storey and Co-Ordination in the building element. Figure 9.8 illustrates the attributes of the building element.

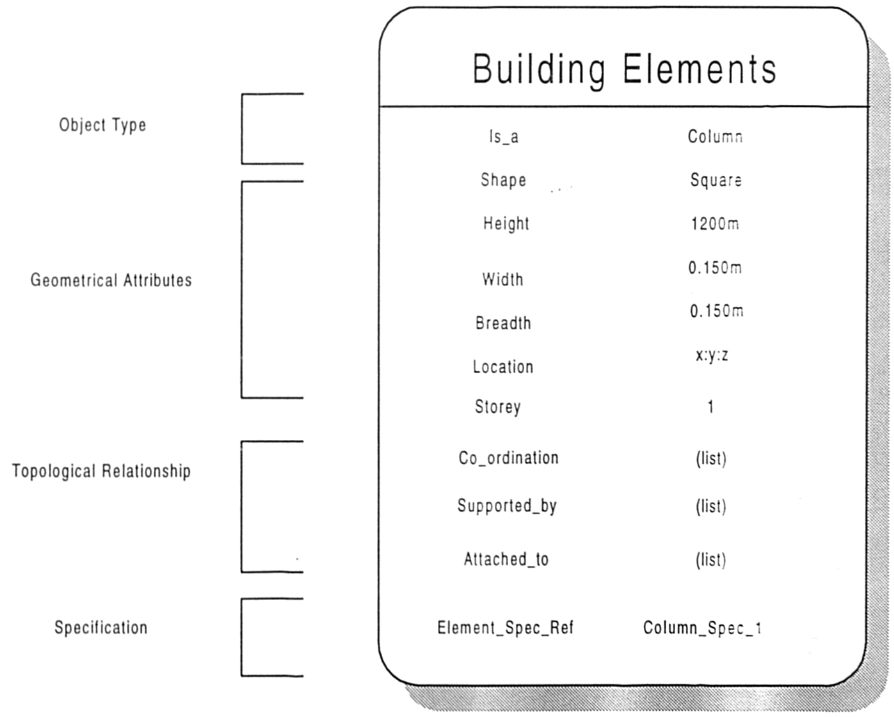


Figure 9.8 The Building Element attributes as produced by CAPE (Che Wan Putra, 1997)

b) The construction activities

In CONPLAN, the Const. Activities object hierarchy consists of various generic activity objects for reinforced concrete building such as Ground Work, Concreting, Moulding, Plastering, Moulding, etc. Figure 9.9 illustrates the construction activities hierarchical objects as modelled by CONPLAN. There are several attributes that have been defined to store the descriptive knowledge of the construction activity objects.

These attributes are SPJIdentity, Required_By, Activity_Names, Sub_Tasks, Predecessor1, Predecessor2, LinkTypePredecessor1. LinkTypePredecessor2, SPJDuration, DateBegin, DateEnd, Plant_Used, Equipment_Used, Quantity_of_Work, Gang_Name, Const_Cost. Unit_of_Measurement, Work Section, etc. These established attributes are also determined to support other applications in the integration environment. Figure 9.10 depicts most of the attributes inherited by construction activities objects from their super classes.

The SPJIdentity attribute describes the name of the construction activity object as displayed in the project management software. The Required_By attribute value refers to the name of the building elements instance for which the construction activity is being created.

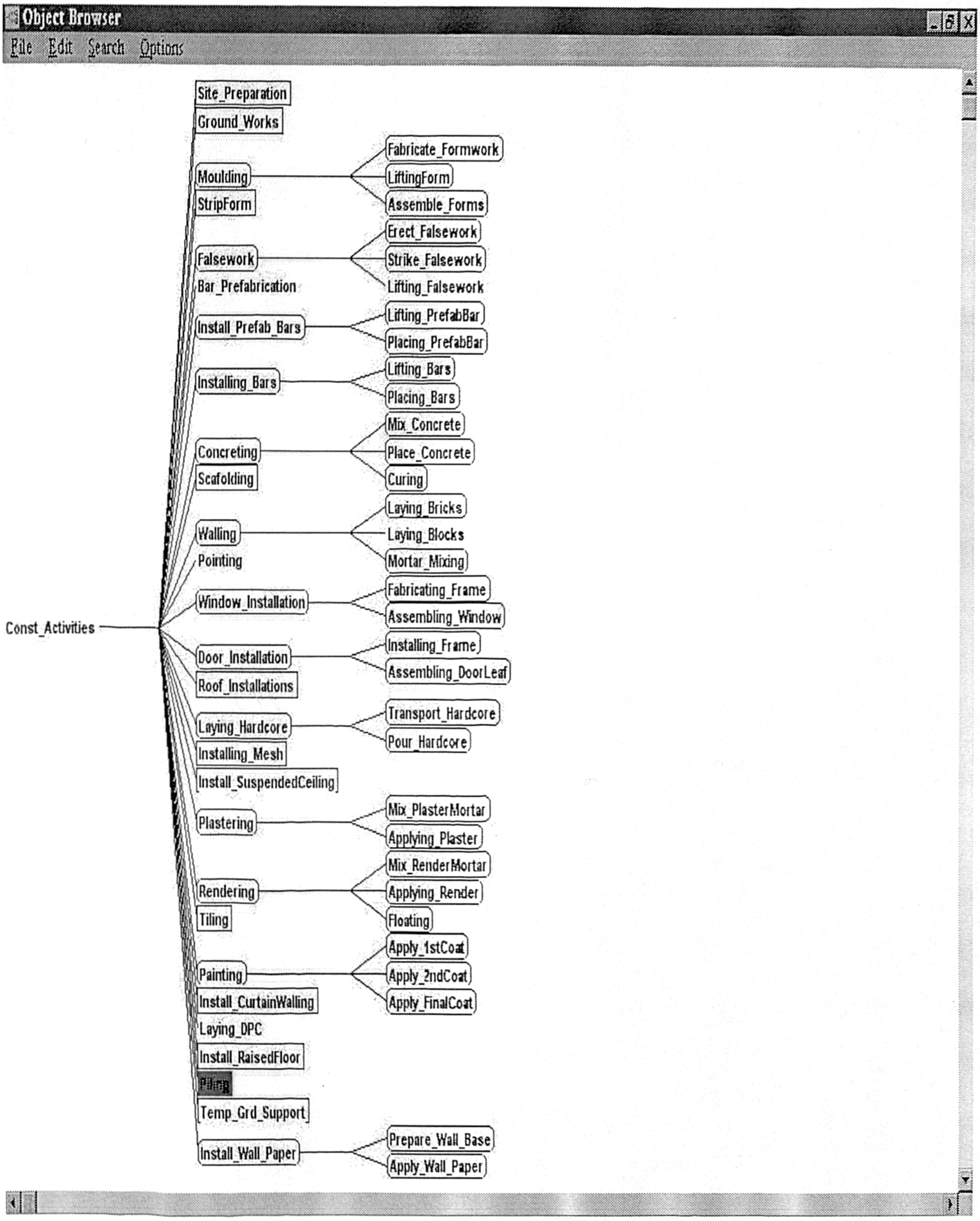


Figure 9.9 The construction activities object hierarchy.

The Activity_Names attribute represents a list of the decomposed project specific construction activities from the generic construction activities hierarchy. For example, Const_Column_1, will have the Activity_Names attribute values such as Installs_Prefab_Bars_Colum1, Moulding_Column1, etc. The Sub_Tasks attribute refers to the type of construction activities likely to be the decomposition activities of the parent activity. Predecessor1 and Predecessor2 attributes value highlights other construction activities which need to be completed ahead of the construction activity object. The former type of predecessor contains construction activities dependency based on physical relationships while the latter is based on resources. Their link types are described in LinkTypePredecessor1 and LinkTypePredecessor2 attributes.

The SPJDuration, DateBegin and DateEnd attributes, contain values obtained from the project management software. SPJDuration represents the construction activity duration, DateBegin highlights the date start of the construction activity, while DateEnd describes the finish date of the construction activity. Plant_Used attribute contains information about what types of plant are established to perform the construction activity. A method to calculate the duration of the activity, using the selected construction methods (plant, facility and labour) is attached in this attribute. The Equipment_Used attribute contains the tools and equipment which would be used by the trade engaged in the construction activity. Gang_Name refers to the type of skilled worker engaged for the construction activity. The value of this attribute is determined by a method which identifies the type of skilled worker required by the construction activity.

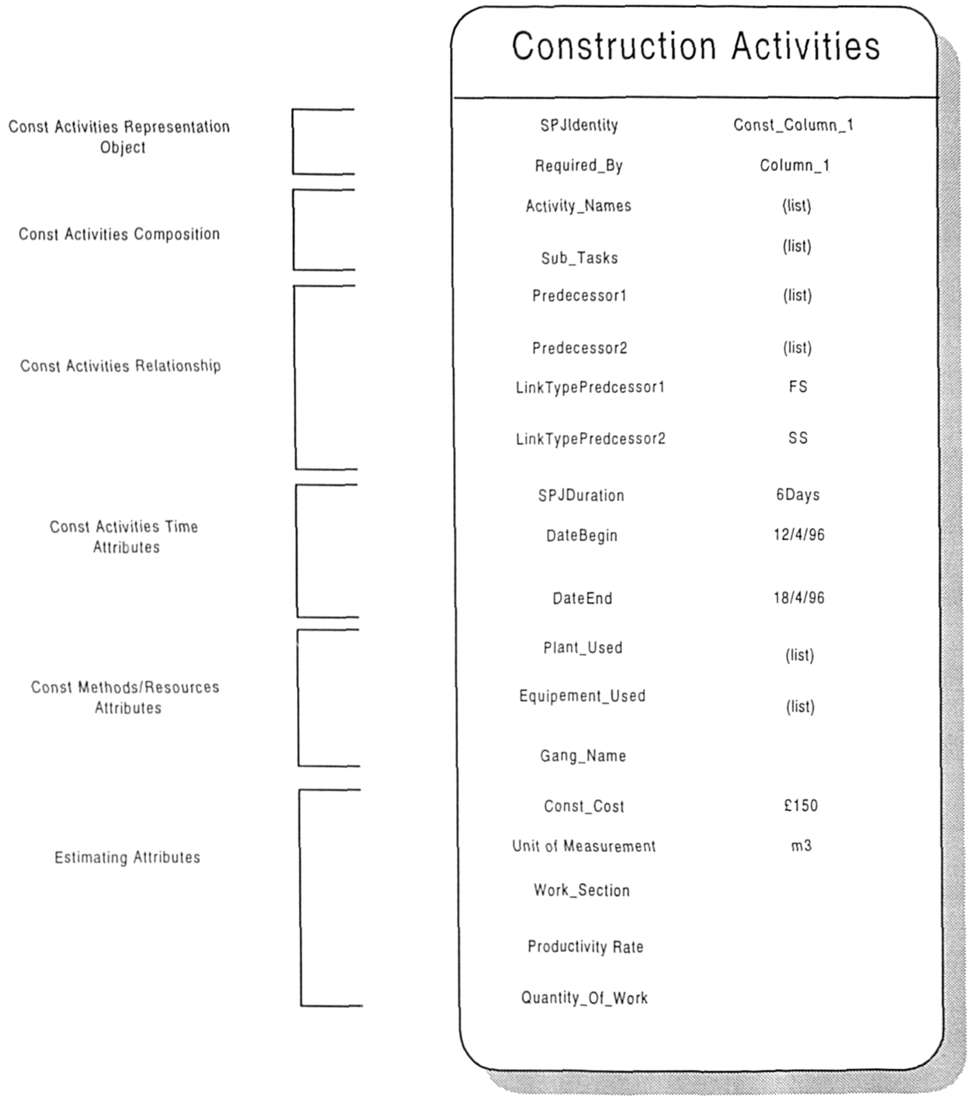


Figure 9.10 The common attributes inherited by Construction Activities objects.

The Const_Cost attribute value contains the estimated cost of the construction activity. The value of this attribute is obtained after all the resources required and duration for the construction activity are established in the construction plan. The Unit of Measurement attribute describes the measurement of the activity from the Standard Method of Measurement (SMM7, 1987), while the Work-Section contains the code of the construction activity as outlined by the Building Project Committee for work sections for building (CPI, 1987).

A specific construction activity object is instantiated based on the descriptive knowledge of its related building elements object e.g. Const_Column_1 is instantiated from the building element Column_1. In order to associate this specific construction activity to its building element, CONPLAN creates several attributes in the building element object such as Construction_Activities, Elements_Quantity, SPJIdentity and Construction Cost. Figure 9.11 present the additional attributes created in the building elements object by CONPLAN's knowledge structure. The Construction_Activities attribute contains the types of specific construction activities which the building element object requires. CONPLAN further decomposes these activity lists into further details. The instances created in this hierarchy represent the specific construction activities for the building element objects.

The Element_Quantity attribute is created to store the amount of workload calculated from the building element. This value is later used by CONPLAN to derive the duration of the construction, once the resources are allocated. To cross-reference the construction activity name to its building element from a construction plan, the value of the SPJIdentity attribute is established. This value of the attribute will uniquely represent the construction activity required by the building element in the construction plan. It will also be instantiated as part of a construction activity object in the Project Const. Plan hierarchy under Const. Elemental Plan.

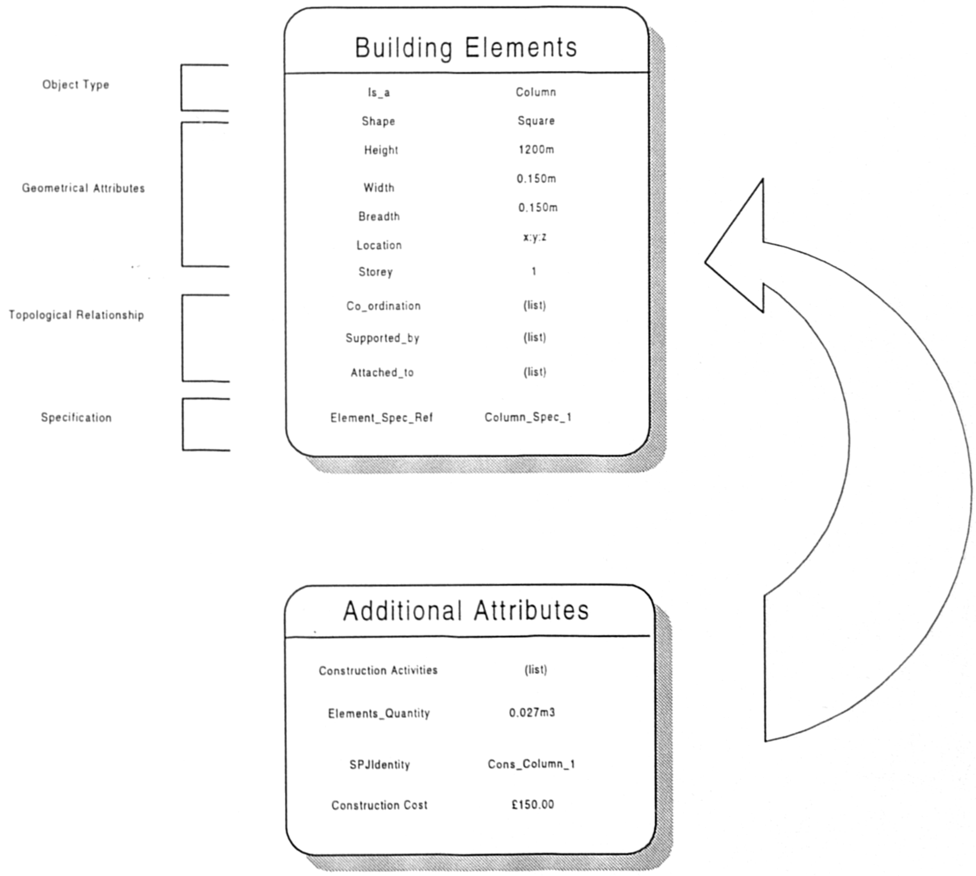


Figure 9.11 CONPLAN created attributes in the building element object.

c) The project construction plans

The object Project Const. Plans object hierarchy is required to define the various levels of detail of the construction plan i.e. the Const. Tasks Plan, Const. WorkPackages Plan, Const. Elemental Plan, Const. Milestone Plan, Const. Zones Plan and Const. Phases Plan. The Const. Tasks Plan is the lowest level of construction activity that can be represented by CONPLAN. Some of the construction activities at this level are such as Fabricate Formwork, Lifting Formwork, Laying Brick, Mortar Mixing, Mix Concrete, Place Concrete, etc. The basic construction resources and their related construction methods are allocated at this level of construction activity representation.

The Const. Workpackages Plan represents the collections of the construction activities from the Const. Task Plan. The WorkPackage Plan is represented by construction activities such as Concreting, Moulding, Walling, Plastering, Falsework, etc. These activities are established from the Construction_Activities attribute of the building element objects. When these construction activities are decomposed, it will produce all the construction activities for the Const. Task Plan.

The Const Elemental Plan contains all the general construction activities which are developed based on the elements of the building. Objects are created by combining which combines the word "Const" in the building elements name to represent the building elements construction activities.

For example, Const_Column_1, Const_FlrSlab_2, etc. When some of these elemental construction activities form a group of work according to the availability of the contractor's resources and site space, such groups will represent the grouped activities in the Const_Milestones Plan. Similar principles of aggregation are applied to the construction activities in the Const Milestone Plan, Const Zones Plan, and Const Phase Plan. When they are aggregated upward (Figure 9.4), they represent higher level of construction information.

Additional attributes are created in these activity representations to establish the component_of relationship between higher and lower levels of construction plans, such as Activities_Names and Part_of. The Part_of attribute value indicates to which high level construction activities representation does the lower activity belong to, while the Activities_Names attribute describes the various low level construction activities contained by the activity.

d) The construction resources

The construction resources knowledge structure in CONPLAN defines the various types of resources which are used by the construction activities. The resources knowledge structure is divided into two categories; consumed and applied. The applied resources structure is further divided into three type of resources, i.e. plant, labour and temporary facility. The consumed resources are the material types which are consumed by the construction activities.

This information is obtained from resources databases and the material specifications. Instances of the applied resources are created when the user selects the resources from their database files. For the consumable type of resources, CONPLAN refers to the specification attributes of the building elements knowledge structure. Figure 9.12 shows some of the attributes used by CONPLAN to obtain information of the construction resources.

The Daily_Cost attribute value reflects the cost of the labour per day, the Labour_Type attribute value represents the skill type of the labour, Number_Available attribute value indicates how many of the labourers are available, Task attribute values represents the type of construction activity the labourers are employed for, while Work_Area attribute value indicates the space required for labour to perform the construction task. This attribute value helps CONPLAN to decide the activity dependency based on space constraint.

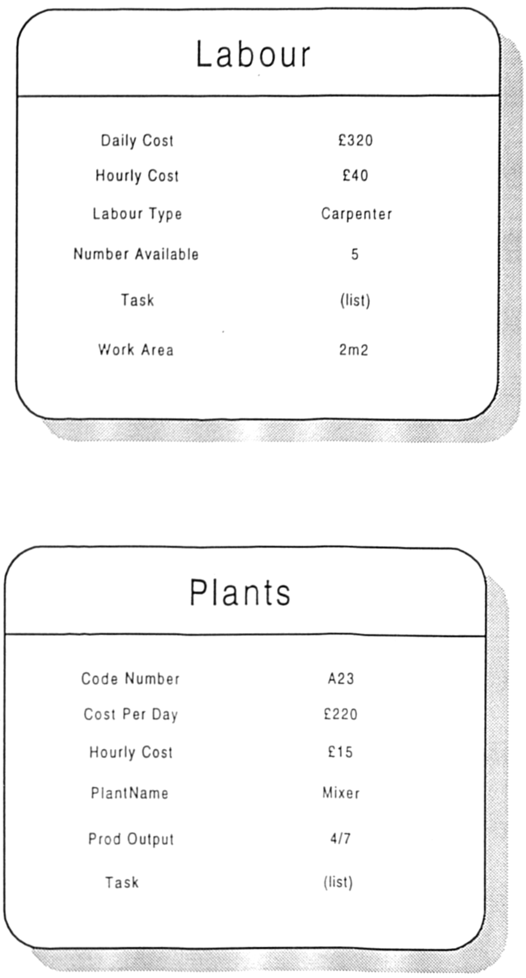


Figure 9.12 : The resources attributes used in CONPLAN

e) Construction options and construction methods

The construction options and construction methods represent the type of resources which are applied to a construction activity. However, the construction options contain various alternatives of the construction methods which are applicable to a particular construction activity. The construction methods can range from lifting construction material, transporting material, mixing or batching concrete or mortar, excavating work, etc., while the construction options used for lifting construction materials can be any of these choices i.e. cranes, lifts, hoists, etc. Similarly, mixing concrete can be either site mixed, where a variety of mixers can be selected or ready mix where different types of plant capacity are available. Each of the construction methods has attributes that describe the type of resources required such as plant type, labour type, and the type of construction activities it can perform.

Since, CONPLAN's construction activity knowledge structure can be defined at a very low level, most of the construction activities represent their construction methods. For example, lifting reinforcement bars, mixing concrete, etc. The associated resources of the construction method i.e. plant and labour applied for these construction activities are described as attributes such as Plant_Used, Equipment_Used and Gang_Name in the construction activity objects. Plant_Used attribute values represent the type and number of plant, the Gang_Name attribute value suggests the type of labour or skill worker assigned, while Equipment_Used attribute values define the tools used by the operator for the activities.

f) Buildability evaluation

The buildability evaluation is performed based on the building elements specification, repetitiveness, assembly, resources usability and variability, process flow, topological dependency and storage requirements as explained in Chapter 7. Since the proposed buildability evaluation will be carried out for each of the building elements, its knowledge representation is developed as attributes of the Building Element object. Some other buildability evaluation factors presented in the Building Element object are DimenPercentageReptn, MatPercentageReptn, DryWetProcess, FalseworkUtilisation, FormworkUtilisation, Number_Of_Assembly, etc. Each of the attributes will be valued according to the principles and equations proposed in Chapter 7.

The value of these attributes depends on the constructional data of the element and on its construction plan. For example, to evaluate the trade utilisation of the building element, its Const_Activities attribute value is first accessed. The value contained in this attribute leads the evaluation process on the various construction activities objects used by the building element. From these construction activities objects, the process then evaluates the Gang Name attribute value and produces a trade utilisation profile. A percentage value will be presented in the TradeFlowPecentage attributes of the building element object.

9.4.3 Knowledge processing

In general the knowledge processing in CONPLAN acts as an information collector, generator, evaluator and developer. When the building model in SPACE has been populated, CONPLAN collects the static information from each of the building element object`s attributes and interprets them using declarative rules into construction knowledge. Once complete information is established, CONPLAN generates other required information such as adding new values to the building element attributes, or instantiating building element components, or creating new instances in any of the objects class representing the construction planning process, e.g. creating specific construction activities, construction resources, or construction plan representations.

Based on these additional values and instances. CONPLAN further evaluates the information before producing any of the required output. To facilitate the various kinds of knowledge processing tasks in CONPLAN, various knowledge processing facilities were used in the development environment such as functions, methods, monitor. message passing, input interfaces, etc. The knowledge processing developed using these facilities was formulated using both procedural and declarative rules. Some of the most important knowledge processing aspects performed by CONPLAN are:-

1. Determine the general construction activities for an element

The process of determining the construction activities for a building element starts when the building element attributes values have been established, such as geometrical, topological and material specifications. CONPLAN uses these attributes value to establish the constructional perspective of the building element. Declarative and procedural rules have been developed to search the design attributes and create the specific construction activities. Below are some examples of procedural rules used to establish the required construction activities for a column and beam.

IF x Is a Column

AND x Material specification is a Cast in Situ Reinforced concrete

THEN x Construction Activities are Moulding, Bar Fabrication, Installing Bars, And Concreting

IF x Is a Beam

AND x Material specification is a Cast in Situ Reinforced concrete

AND x Level is not less than 1

THEN x Construction Activities are Falsework, Moulding, Bar Fabrication, Installing Bars And Concreting.

IF x Is a Beam

AND x Material specification is a Cast in Situ Reinforced concrete

AND x Level is less than 1

THEN x Construction Activities are Ground Works, Moulding, Bar Fabrication, Installing Bars And Concreting.

2. Developing the representation of the construction activities

There are several levels of detail of construction activities which can be represented by CONPLAN, e.g. Const Task Plan, Cons WorkPackage Plan, Const Elemental Plan, etc. As described earlier CONPLAN adopts middle-down-and-up approach when developing the various levels of the construction plan. Firstly, CONPLAN establishes the elemental construction activity for each of the building element objects. These general elemental construction activities representations are established by adding an event object "Const" to the building element object e.g., Column_01 will become Const_Column 01.

Secondly, the sub activities are established using the values from the Construction_Activities attributes in the building element object. For example Const_Column_01 will have sub activities Moulding_01, Bar Fabrication_01, Installing Bars_01, And Concreting_01. These sub activities are created as instances in the Construction Activities object hierarchy. This level of construction activities abstraction is part of the Const_WorkPackage

Plan while all the elemental construction activities represent the Const_Elemental_Plan.

Each of the Const_WorkPackage Plan instances has its own knowledge to generate further sub activities based on its own hierarchical structure. For example Moulding_01 generates its sub activities such as Fabricate Formwork 01, Lifting_Formwork_01 and Assemble_Formwork_01, while Installing Bars 01 generates its sub activities such as Lifting Bars_01 and Placing Bar 01. This lowest level of activity representation is called Const Task Plan.

At this level, each construction activity is allocated with specific methods to calculate the volume of work to be undertaken by the activity, select the type of plant, calculate duration, and determine its predecessor. Each of these methods varies according to the type of construction activities and the building element object it represents. For example if the construction activity is Place Concrete 01, then the quantity of work will be represented by the quantity of concrete calculated for Column_01, while if the construction activity is Fabricate_Formwork_01, then different calculations will be applied to obtain the quantity of work.

Once the lowest level of construction activities are established from the elemental construction activity representation and the construction solutions to the activities are formulated (e.g. selection of construction methods, quantity of work and duration), CONPLAN further establishes the higher level of construction activity representation based on the availability of resources and space. All elemental construction activities are grouped according to these factors and formed into Construction Activity Milestones, which becomes part of the Const_Milestone Plan.

3. Allocate the required construction resources and methods

When the representations of all the low level construction activities have been developed, CONPLAN assigns the applied resources to these activities. The allocation of the resources is performed in two ways either through user selection or automatically recommended by CONPLAN. When the user selects to define the construction methods and/or resources. CONPLAN acts as a facilitator by displaying the workpackages, the construction activities being interrogated, and the available types of plant. During this process, the user is expected to have some construction planning knowledge for making the selection which is based on the available resources on the databases.

If the resources are to be selected by CONPLAN, a method which is assigned to the attribute Plant_Used in the construction activities objects will be invoked. This attribute when assessed will invoke a method to select a suitable plant. The labour requirements are also assigned during this stage. The type of the construction activity being interrogated will determine what type of labour would be required. For example if the activity is Concreting, then the type of labour associated with the work is Concretor, or if the activity is Fabricating Formwork, then the labour type is Carpenter, or if the activity is Lifting Concrete by crane then the labour type applied is Crane Operator.

The amount of labour assigned to the construction activity will be based on the selected construction method which determines the amount of labour required and the productivity rates being applied. The selection process and the allocation of both plant and labour is based on a common type of plant and labour which is identified and used for a particular type of construction activity. The selection and optimisation process of the plant and labour, however, is dealt with by external applications or users when going through the selection process. An example of the methods attached to the construction activity object is illustrated below;

- For Excavate Soil construction activity

    IF X Construction Activity is Excavate Soil

    THEN Use EXCAVATOR

    SELECT any of the displayed list of EXCAVATOR (Excavator1, Excavator2, Excavator3, Excavator4)

- For Lifting Concrete construct activity

    IF X Construction Activity is Lifting Concrete

THEN Use CRANE

SELECT any of the displayed list of CRANE (Cranel, Crane2. Crane3, Crane4)

- For Mixing Concrete construction activity

IF X Construction Activity is Mixing Concrete

THEN Use MIXER

SELECT any of the displayed list of MIXER (Mixerl, Mixer2. Mixer3, Mixer4)

4. Establishing the logical sequence of the construction activities

The logical sequence of the construction activities in CONPLAN is process based on five dependency factors, i.e. physical, resources, process, safety and space. The physical dependency is established by referring to the topological relationship between the building elements. The resources dependency is determined based on whether any of the construction activities share similar resources.

The process dependency is defined from the production technology of the building element. The safety dependency is established by observing a specific safety rule which is applied to the construction processes, while the space dependency is based on whether the resources for any of the construction activities are hindered by space occupancy. Currently, however, CONPLAN applied four out of five dependency factors in its knowledge processing system. These are the physical, processes, resources and space dependency.

Most of the dependency factors in CONPLAN are determined by functions. The functions are developed based on procedures and rules which facilitate the interrogation of the construction activities, building element's instances and resources. In order to establish the physical dependency factor for the elemental construction activities, a function first refers to the construction activity representation's attribute Required_By to determine to which building element does the construction activity represent.

When the instance of a building element is recognised, the building elements topological attributes which can be either Supported_By or Attached_To are accessed. Using the value from this attribute, the function then finds the described building element object and establishes its construction activity's object.

Once the instances of the above building elements construction activity objects are recognised, a finish to start dependency link will be established between the elemental construction activities objects. Since the determination of the logical sequence of construction activity used static knowledge, a declarative rule is used by CONPLAN to determine the physical predecessor of an element. Below is an example of the declarative rule.

IF x Is a Column_02 And
x SPJIdentity is Const_Column_02 And
x is Supported By Column_01
THEN Get SPJIdentity of Column_01 And
determine x Predecessor

In the case of the construction activities object, since its has a standard sequence of production, the dependency between the construction activities are established mainly based on their production rules. For example, the construction activity 'Mix_Concrete' always precedes 'Place_Concrete' or 'Excavate_Soil' always precedes 'Remove_Soil'.

To determine the dependency based on these production process rules, CONPLAN first establishes the various construction activities represented for the building elements objects. Once the construction activities are recognised, the production process rules which apply to the workpackages and tasks are then used to establish the dependency between these construction activities. Described below are examples of the declarative rules used to determine the construction activities dependency between tasks and workpackages.

IF X Construction Activity is Dump Soil_01

THEN X Predecessor is Remove Soil_01

IF X Construction Activity is Remove Soil_01

THEN X Predecessor is Excavate Soil_01

IF X Construction Activity is Placing Concrete_02

THEN X Predecessor is Mix Concrete_02

Examples of the declarative rules used to determine the dependency between workpackages.

IF X Construction Activity is Install_Prefab_Bars_01

THEN X Predecessor is Moulding_01

IF X Construction Activity is Concreting_01

THEN X Predecessor is Install_Prefab_Bars_01

When two or more construction activities need to share the same resources (plant, labour, work area, etc.), the dependency based on resources has to be established between those activities. Here, CONPLAN first checks if any of the construction activities have a physical or a process dependency established. If the physical or process dependency exists between the activities, then the resources dependency factor will not be considered between these activities.

However, if no dependency exists, CONPLAN will further check whether the construction activities are part of a construction milestone activities representation. If they are not grouped as part of the established construction milestones, then the resource availability for the project is accessed and it is further determined whether they can be shared at once or used subsequently. If the resources could not be shared at one time, and extra resources are not available, then finish to start dependency is selected between these activities. Below is an example of a procedural rule which establishes the dependency between two construction activities which have to use similar resources.

IF X Construction Activity is Dump Soil_02
AND X Use Lorry A
AND Y Construction Activity is Dump Soil_01
AND Y Use Lorry A
AND Resources available is Lorry A
THEN X Predecessor is Dump Soil_01

For the construction activities which are represented as construction milestones in the plan, their dependency is established based on the availability of resources and space. The first construction milestone will have a dependency finish to start type with the next construction milestone if both of the activities share the same resources. For example if there are sixteen columns and only four carpenters are available, and capable of assembling and fabricating eight columns at a time, then two groups of construction activity milestones would have to be established. Based on the availability of the carpenter, the first eight columns have to start and complete before the remaining eight formworks of the columns can be fabricated and assembled.

If there are eight carpenters available in the database, from previous example, all the columns can be assembled and fabricated at once. However, before this decision is taken, CONPLAN will evaluate the space availability at the location of the construction activities (in this case the area of the slab) and the space required by a carpenter to perform his/her task (in this case the Work Area specification from the resources database is accessed) to determine the space constraints.

If the available space can accommodate eight of the carpenters then the construction of these activities can be done all in one group. However, if the space is not enough for all the carpenters, then, two groups of construction activity milestones have to be established and performed in sequence.

5. Calculating the duration and operational cost of the construction activities

There are over 60 types of generic construction activities defined in the construction activities hierarchy in CONPLAN. Each of these activities required different methods for calculating its duration. Since, the best approach to obtain the construction activities duration depends on activity sampling and previous records of construction works, where applicable, CONPLAN uses these two approaches to calculate the duration, i.e. the basic operation times equations (Harris *et al.*, 1985) and the general production rates (Geddes, 1985).

In CONPLAN, these equations are attached as methods to the attribute of the construction activities objects, which when accessed will calculate the duration of the construction activity. Besides these equations. the construction activities attributes values such as Quantity_of_Work and Unit_of_Measurement are also used by CONPLAN to obtain the duration.

An example of the equation (Harris *et al.*, 1985) which shows how the calculation is carried out to obtain the duration for fabricating formwork of an internal beam is illustrated below:-

Basic time for Internal Beam (mins/m) = (3.75 + 2.56 +2.56)1.24 x L

= 11.0 L

where L = Length of internal beam(m)

Make and position bottom shutter = 3.75 min/m2

Make and position side beam = 2.56 min/m2

Allowances for Ancillary Work = 1.24 %

The equation after being developed into a procedural rule in the construction activity object:-

IF	X	is an Internal Beam
AND	X	length is 3 metres
THEN	X	Construction Activity Duration in hours is 11.0 x 3 x 1/60

When the basic operation times equation from Harris *et al.* (1995) is not available for some of the construction activities, CONPLAN uses the general production rate to derive the duration for the activity. For example, from the tabulated production rate of the plastering work (Geddes, 1985) as shown below, a production rule which acts as a method is assigned to the construction activities attribute. The method which is attached to the Quantity_of_Work attribute when changed, will calculate the duration of the construction activity.

	Plasterer Hours	Labour Hours
Render on walls first coat 12mm thick/m2	0.24	0.24
Render on walls first coat 19mm thick/m2	0.36	0.36
Render on walls and float for finishing coat 12mm thick/m2	0.30	0.30
Finishing coat trowelled 6mm thick/m2	0.42	0.42

A production rate of square meter/hours of these works will be multiplied by the square area of the wall and adds up, to obtain the total hours of the plastering work.

IF X is Apply Plaster
AND X Area is 5.0 m2
AND X Layer Thickness are 12, 12 and 6
THEN X Construction Activity Duration in hours is (0.24+0.30+0.42) x 5.0

Other equations and production rates which CONPLAN uses to calculate the duration of other activities are attached in Appendix A.

6. Transferring the construction information to and from an external package.

After all the values of the construction activities attributes have been determined in the knowledge based system, CONPLAN collects the required information and sends it to the project management package to produce and display the CPM network. Amongst the information sent by CONPLAN are the various levels of construction activities objects, their duration, their resources and its cost, and the dependency links.

In order to develop the various levels of construction activities in the plan i.e. detail, executive and master, various knowledge processing routines were developed. Firstly CONPLAN knowledge processing groups the building element's construction activities according to its abstraction. Once the hierarchical structure of the activities representation and the dependency links are established in the knowledge based system, the information is sent to the project management package. CONPLAN will invoke several of the internal commands (through dynamic data exchange (DDE) facilities) in the package to build the network. The construction activities representations are arranged according to its composition hierarchy. The lowest construction activities representation will be attached with the resources information. The dependencies between the lowest activities are first established, followed by the higher representations.

When the network plan is completed, the information derived from the package is retrieved back into the construction activity objects in the knowledge base to form project specific planning information. The available information will then be used by CONPLAN and other applications such as valuation, site layout planning, and for construction simulations. Most of the procedures to generate, send and retrieve information are build as functions in CONPLAN.

7. Developing a buildability profile for each of the elements from the design and construction information.

The knowledge processing for this function acts as a generator as well as an evaluator to produce and evaluate the buildability profile for the building element objects. These tasks can be operated once the construction planning information is made available. Before any buildability value is calculated, CONPLAN creates a number of attributes representing the buildability evaluation factors in the building elements objects, such as DimenPercentageReptn, MatPercentageReptn, DryWetProcess, FalseworkUtilization, ForwmworkUtilization, Number_Of_Assembly, etc. Since the building elements represent high level specification descriptions, CONPLAN also creates new and lower levels of instances of building components based on their combined specifications. Some of these building components are Plaster, Screed, Finishes, etc. As an object, this building components instance facilitates itself to be used for interrogation and storing the buildability factor value when the buildability evaluation is performed.

Several functions have been developed to evaluate the buildability aspects of the building elements and to produce the quantitative value for the attributes has been described in Chapter 7. Some inputs are required from the user/evaluator when CONPLAN performs the buildability evaluation. When evaluating the buildability aspects, CONPLAN refers to the building elements attributes value, such as its dimensions, topological relationships, specifications, location, quantity, etc, and its construction activities attributes such as resources used, process dependency, cost and duration.

Once the values for the proposed measurements (in Chapter 7) are obtained, CONPLAN tabulates the result in a line graph and textural format and displays the building elements objects which are subjected to the evaluation on the virtual reality tool.

9.5 CONPLAN system interaction

CONPLAN interacts with almost all the application data modules of SPACE and its external packages. The interaction occurs in various aspects of CONPLAN's knowledge representation and processing. Figure 9.13 depicts the conceptual interaction which takes place when CONPLAN is in operation.

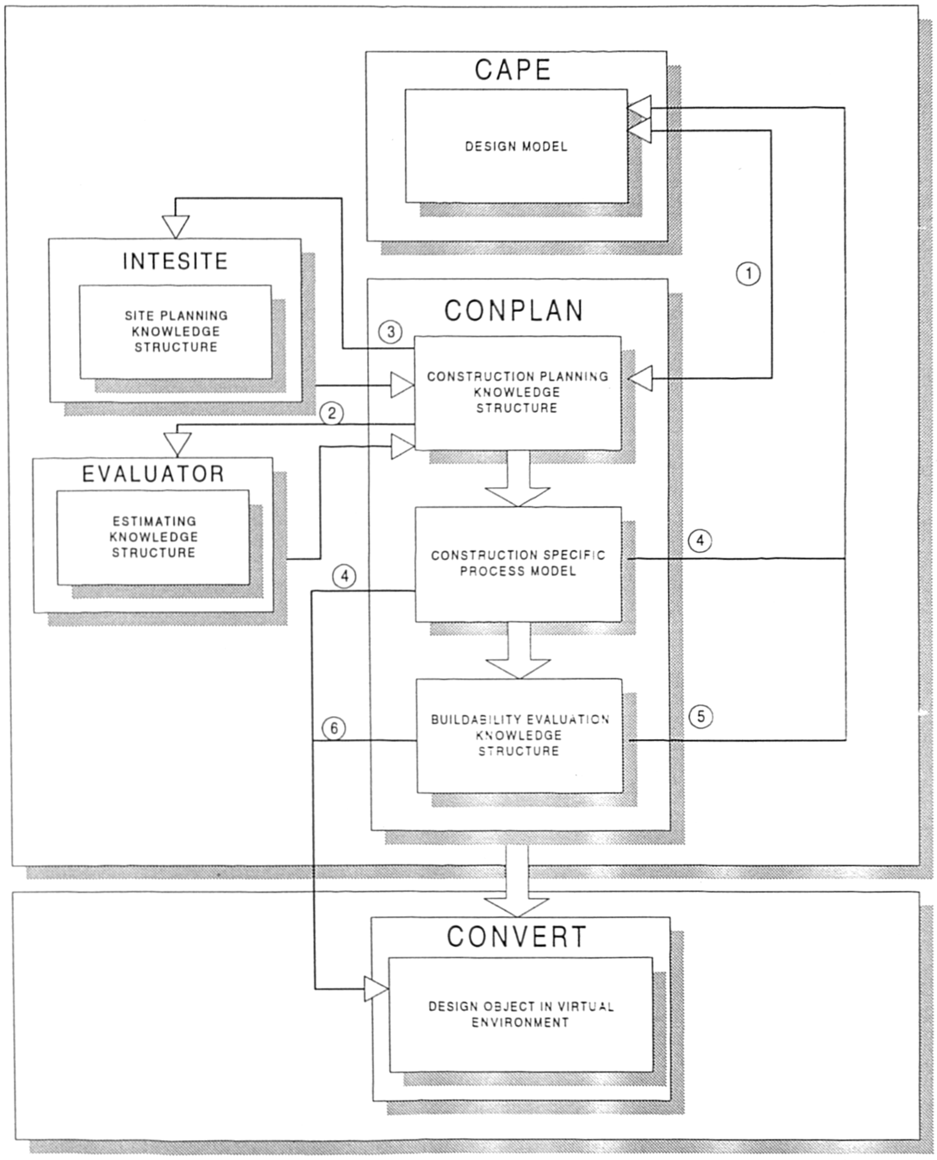


Figure 9.13 CONPLAN system interaction processes

The first interaction (1) starts when CONPLAN's construction planning knowledge structure refers to building module from CAPE to establish the construction activities required for each of the building element objects. At this interaction stage, information is exchanged between the knowledge structure of building element objects, and the generic construction activities objects hierarchies. The product of the interaction is the generation of specific construction activities objects. This product will be part of the construction specific process model for the building.

The construction planning knowledge structure which facilitates the resource allocation process will interact with its resources knowledge representation to allocate the required resources for the created construction activities objects. To obtain the estimating data and apply the resources to the construction specific activities objects, the construction planning knowledge structure consults (2) EVALUATOR (Underwood& Alshawi, 1996).

Once the specific construction plan is developed for the building module, some of the attributes of the construction activities are represented in the building element objects. This initial construction plan (3) will be sent to the INTESITE for site layout planning evaluation (Sulaiman, 1997) and EVALUATOR for validation. To visualise this initial construction plan, CONPLAN will interact (4) with CONVERT (Alshawi & Faraj, 1995) and simulate the construction plan.

If the initial proposed plan is conflict with INTESITE or EVALUATOR, the initial plan will be reformulated based on the given constraints. Once the final construction plan is available, it can be simulated again (4) in the virtual environment. The final construction plan will also be interacted by the buildability evaluation knowledge structure to produce the buildability reports. The building module in CAPE is referred to by the buildability evaluation knowledge structure (5) to execute its evaluation processes. After the buildability evaluation knowledge structure has produced the results, CONPLAN will further interact (6) with CONVERT to highlight in a virtual environment, the considered building elements from the buildability evaluation report.

9.6 CONPLAN system application

CONPLAN was developed as an application in the SPACE integrated environment. Its major functions are to generate construction plans, provide the necessary planning information for other construction applications such as site layout planning, estimating, construction project simulation, etc. and perform buildability evaluation for the design solution. Before CONPLAN can be operated from the SPACE interface, the building module has to be populated with the design information. This will provide CONPLAN with the basic input it requires to perform its functions. Figure 9.14 shows the main interface of the SPACE integrated environment which includes a list of various buttons, to activate the various construction applications.

To invoke CONPLAN the users/evaluators simply has to click on the 'Planning' button of the SPACE main interface. This will lead the users/evaluators to CONPLAN's main pop-up menu which highlights its definition and its sub options menu.

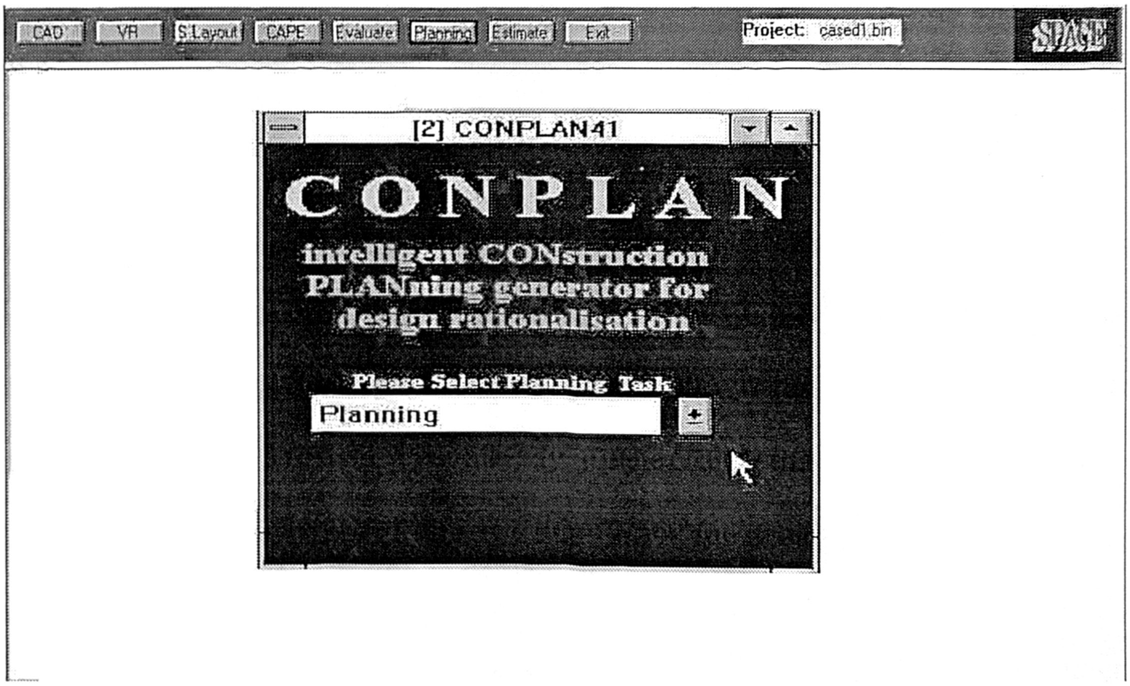


Figure 9.14 The opening screen for CONPLAN in SPACE system integration.

9.6.1 Generating the construction plan

The system starts by asking the users/evaluators to select the required functions i.e. 'Planning', 'Replan' and 'Exit Planning'. The 'Planning' function is selected when the construction plan and construction resources are required to be established. The 'Replan' option however is designed for the users/evaluators to run CONPLAN again from previous planning trials, and/or after making changes to the building elements, or to the type of resources. The 'Replan' option significantly reduces the time required to generate plan as it only deals with the changed information. The 'Exit Planning' option however, is designed to allow users/evaluators to quit the system. By selecting this option, CONPLAN will close the project management software as well as the interfaces used by CONPLAN.

When the 'Planning' function is selected, CONPLAN automatically loads the project management software (CA-SuperProject™). When the 'Replan' function is selected, CONPLAN assumes that the project management software is already opened and that objects are populated with all the required information. When the project management software is loaded, the users/evaluators is asked to select the required level of planning information, i.e. Master Plan, Executive Plan and Detail Construction Plan. The Master plan provides strategic information of the construction work, the Executive plan shows more detailed information which is useful to managers, while the Detail construction plan produces all the elements of Master plan, Executive plan and the lowest detail of the construction information.

Since the detail plan produces the lowest level of detail of the construction information, considerable time is taken by CONPLAN to generate this type of construction plan compared to the other types of plans. However, this detailed information is required to support other applications in the SPACE integrated environment. When a type of construction plan is selected, users/evaluators are asked whether any of the building element finishes have been changed. The answer given by the users/evaluators allows CONPLAN to make any adjustment, or reset the specifications of the previous finishes, if changes have been made. The operation will trigger CONPLAN to collate, create and develop all the necessary information which is required by the construction plan. At this stage a message will appear on the screen informing the users/evaluators that CONPLAN is "operating".

When CONPLAN reaches the point where construction resources are required to fulfil its objectives, users/evaluators are asked to identify the location of the resources files, Figure 9.15.

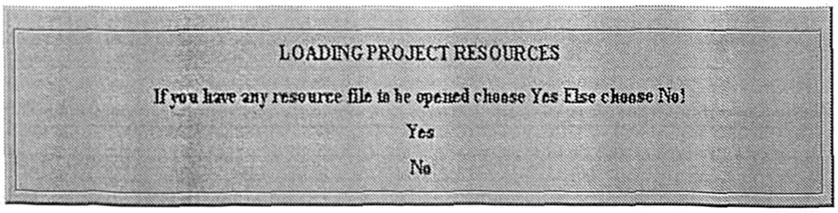


Figure 9.15 The interface for loading resources into CONPLAN

The resources are used by CONPLAN to generate the construction plan. If an identical resource file has already been referred to by CONPLAN, the users/evaluators will be told that the resources have been loaded in the knowledge base and the system will ask whether the users/evaluators need to open any other resources file. Once CONPLAN arrives at a stage of resources selection, an option is given to the users/evaluators whether the process should be executed automatically or selected by the users/evaluators, Figure 9.16.

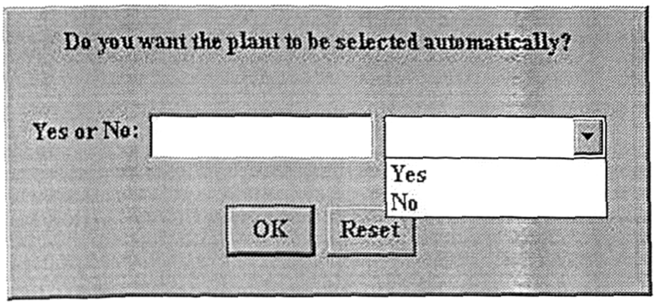


Figure 9.16 The users/evaluators selection for resources allocation.

When users/evaluators select 'No', CONPLAN opens an interface window which displays construction activity and plant specifications. CONPLAN will scroll through the required construction activities and ask users/evaluators to select the resources type, Figure 9.17. Once all the resources have been allocated to the construction activities, CONPLAN asks whether users/evaluators would like to view a report of the plant and the associated labour that have been selected earlier. When a "Replan" function was chosen, the users/evaluators could change the amount of the labour employed from Figure 9.18.

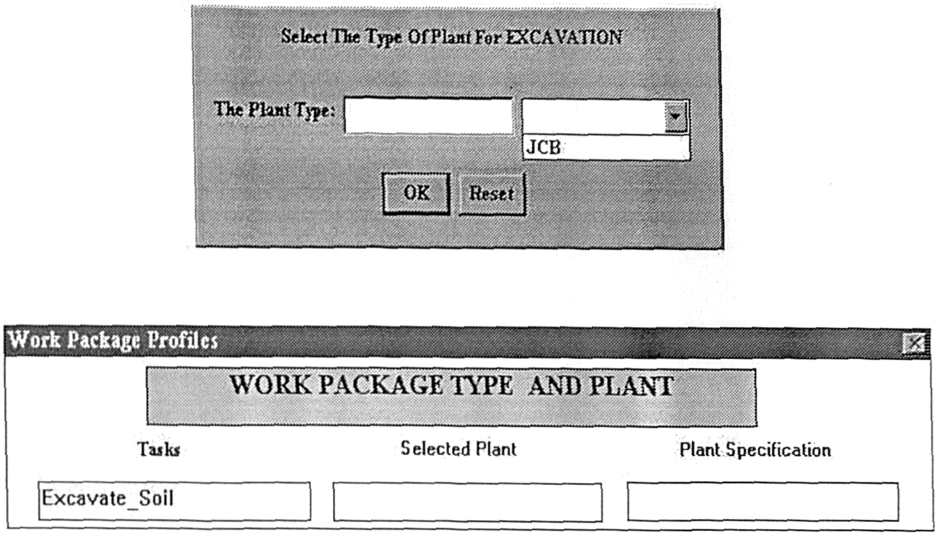


Figure 9.17 The interface for selecting the required resources.

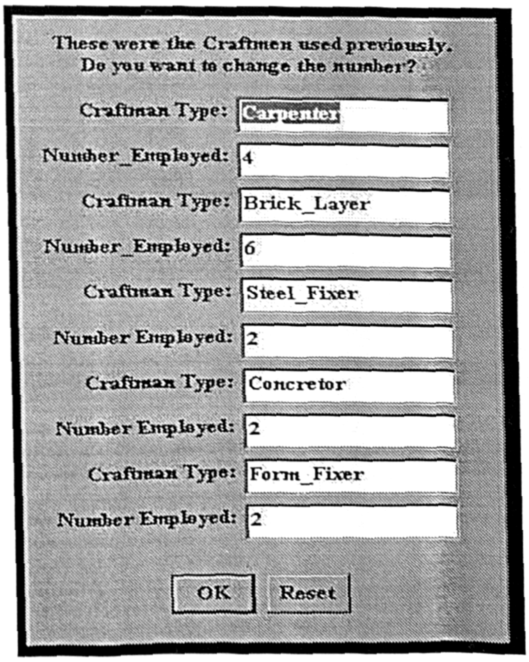


Figure 9.18 The interface for changing project resources.

Several post messages will appear on the screen which would request users/evaluators to acknowledge the system in operation. An interface window 'CONPLAN 43' will appear showing a summary of the allocated resources (craftsmen and labour) in a group, for the main construction activities, Figure 9.19.

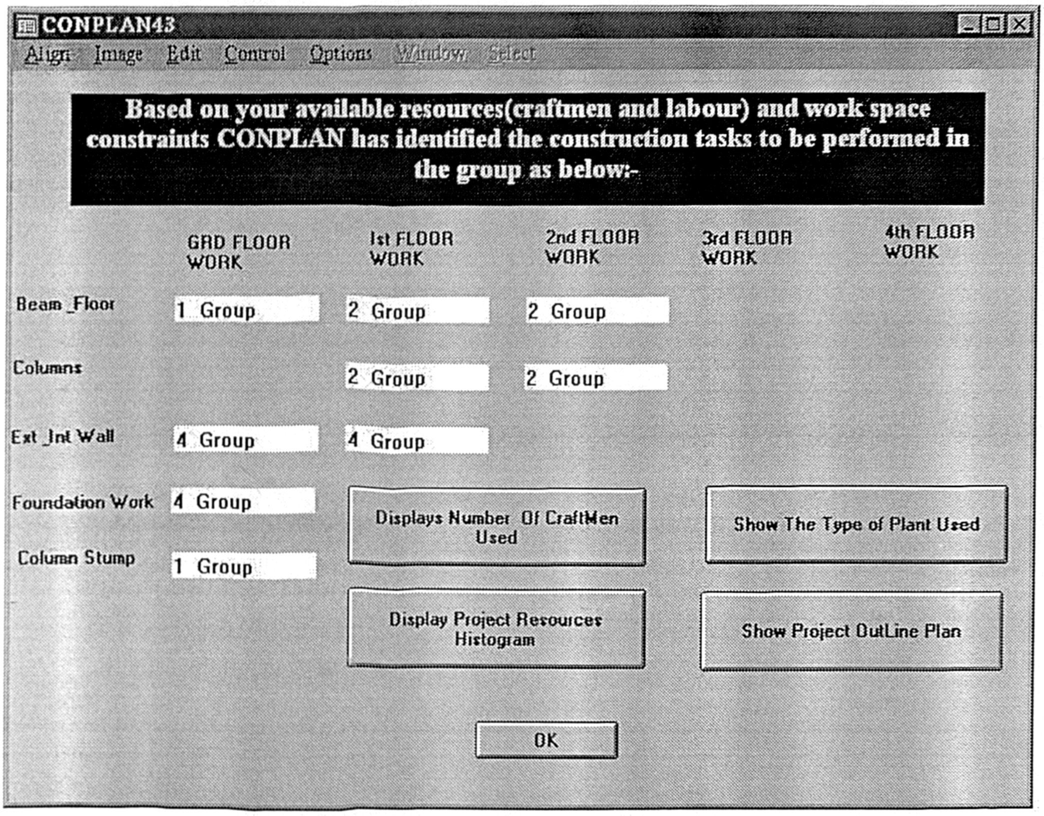


Figure 9.19. The construction planning report interface

Several other buttons are presented on this interface for users/evaluators to view other types of construction planning reports when the process is completed, such as the construction plan, resources profiles, plant and labour reports. Several post messages will appear on the screen notifying the users/evaluators of the stages of developing the construction plan. Once the construction plan is developed, users/evaluators can view the various parts of the plan such as the resources profile, project cost and s-curve, etc., as provided by the CONPLAN interface in Figure 9.19, or directly using the project management system. Figure 9.20 and 9.21 below show an example of a construction plan and resources profile generated by CONPLAN.

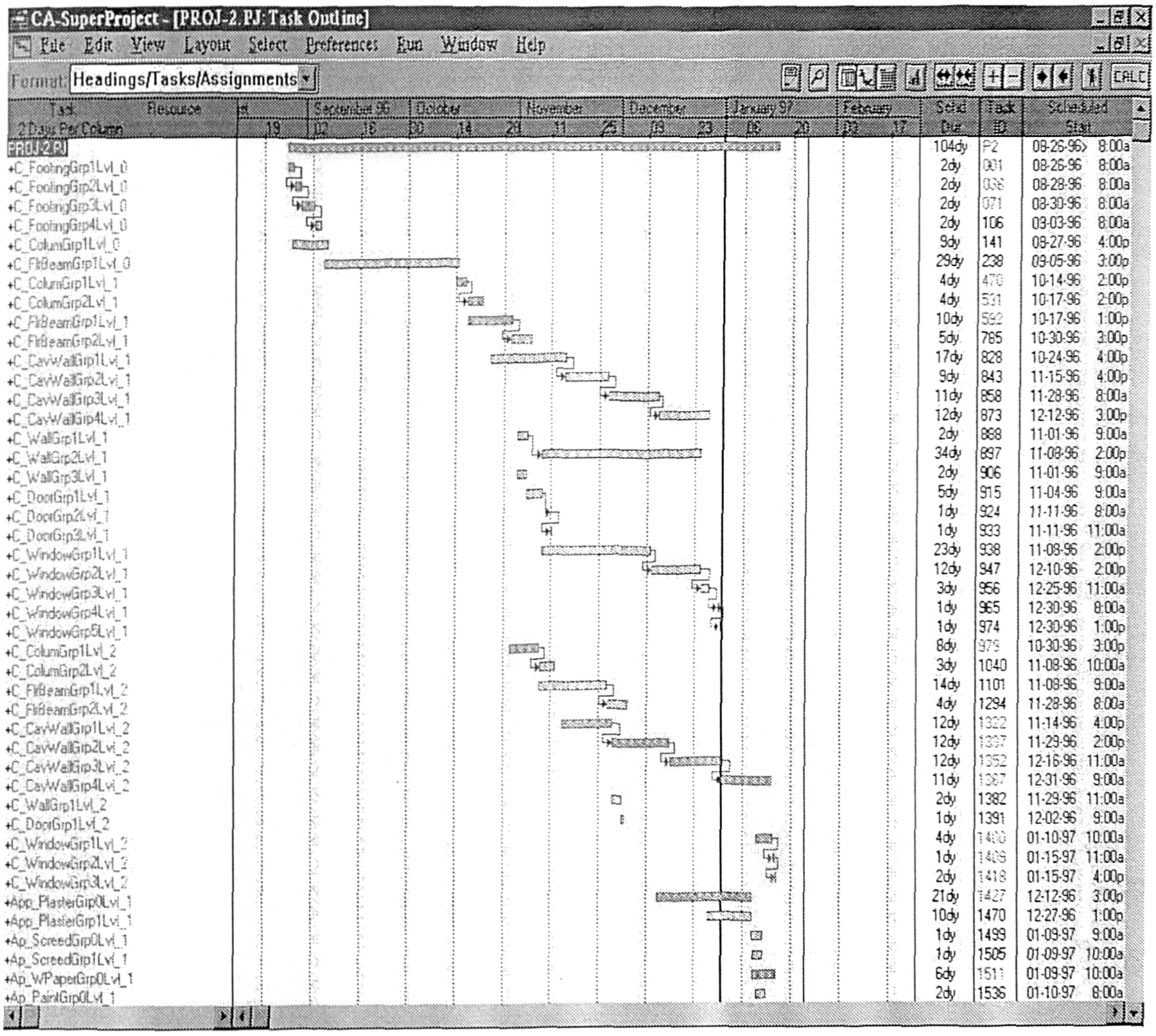


Figure 9.20 An example of construction plan on the bar chart format.

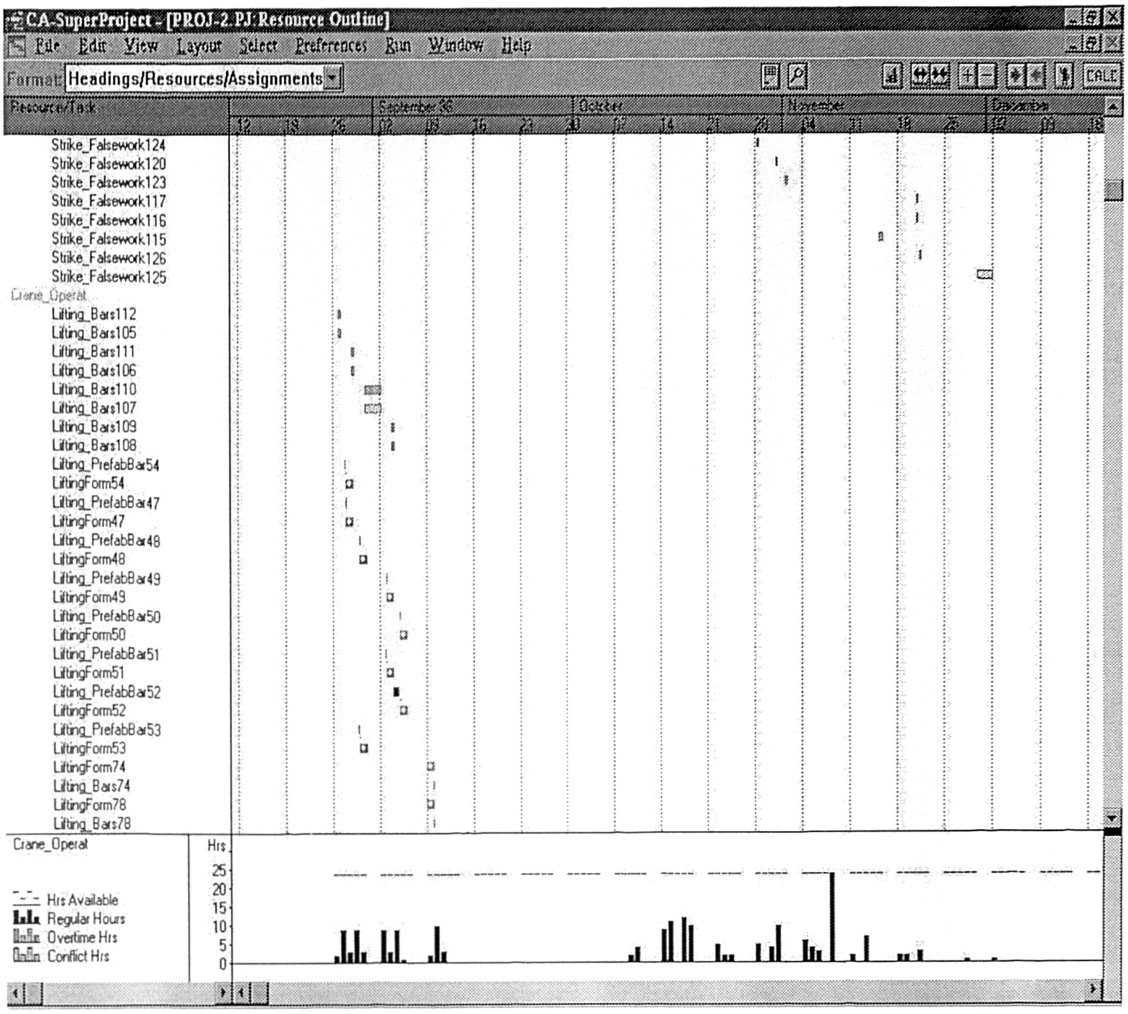


Figure 9.21 Example of the construction plan resources profile.

9.6.2 Construction Simulation

Once the generated construction plan is developed, a project construction simulation can be performed by CONPLAN. The main menu of CONPLAN shows two functional buttons underneath the combo box, Figure 9.22. The functions of the 'Show construction simulation' button is to simulate project construction on a virtual reality tool. The simulation is designed to show the construction progress on a monthly basis. When the users/evaluators click on this button, a small window interface will appear which has a slider image and 'Show construction as planned' button.

Figure 9.22 CONPLAN main menu with construction simulation and buildability evaluation buttons.

The slider is designed as a scale for the users/evaluators to mark the length of month the construction process can be simulated, Figure 9.23. The numbers appear on both ends of the slider, indicate the scale of the construction period derived from the construction plan in the month. Users/evaluators can move the slider button from left to right to mark the length of the simulation required. A number underneath the slider will change accordingly to mark the month of simulation the users/evaluators selects. In order to simulate the construction process, users/evaluators have to open the virtual reality tool from the SPACE interface screen by clicking on the 'VR' button. The virtual reality tool facilities which are designed by CONVERT (Alshawi & Faraj, 1996) will provide the communication link to open and operate the tool.

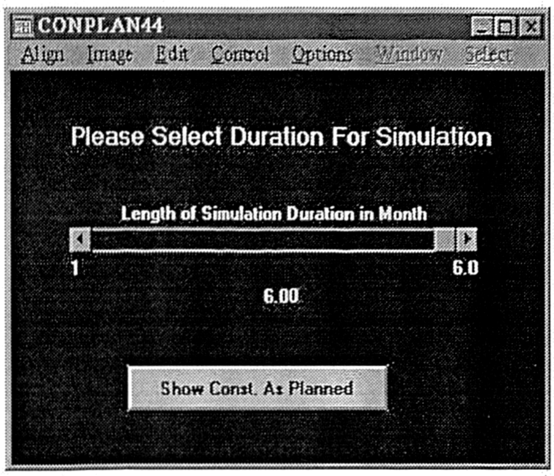


Figure 9.23 The construction simulation users/evaluators interface.

A post message will appear when the users/evaluators clicks the 'VR' button, requesting the users/evaluators to acknowledge the process of connecting the virtual reality tool and building element object through the DXF files. Once the building model appears on this tool, the users/evaluators can adjust the orientation of the building model using the menu facilities developed by CONVERT.

To simulate the construction processes, the users/evaluators have to set the length of duration required using the slider as shown in Figure 9.23. Once the duration of the simulation is determined, the users/evaluators have to click on the 'Show construction as planned' button to view the simulation in stages. Only construction activities which directly represent the building elements will be shown on the simulation. Therefore, on the first month of the simulation, nothing will appear on the screen, since the activities which were planned on the first month were usually the site preparation activities i.e. excavate ground, etc.

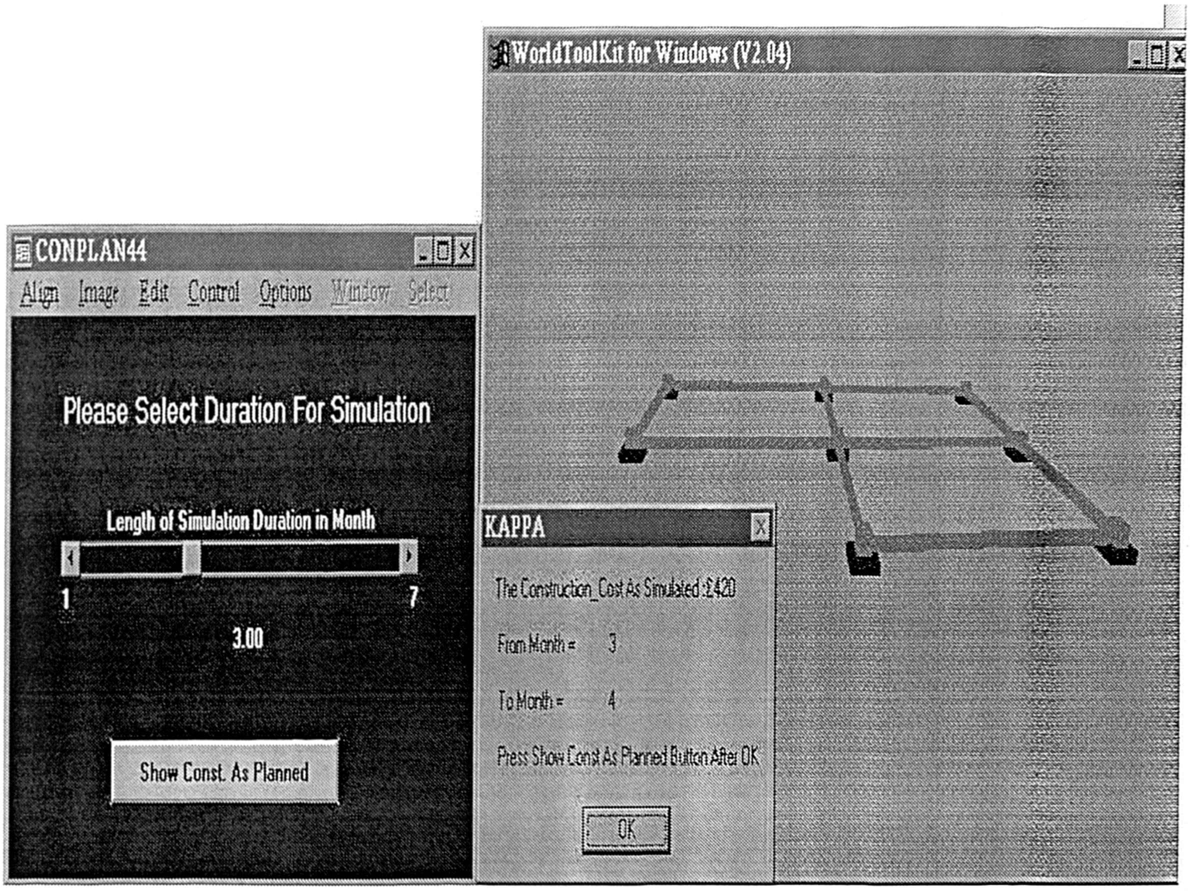


Figure 9.24 A cost report for the simulated month.

A construction cost report based on the simulation period will appear before the actual building model in the virtual reality tool, Figure 9. 24. When the users/evaluators press 'ok' on the cost report interface, the building model will appear. Users/evaluators can walk through the building model while the simulation process is progressed to visualise the construction work as indicate on the construction plan.

9.6.3 Buildability Evaluation

The buildability evaluation in CONPLAN can be performed, once the construction information from the project management software has been extracted into CONPLAN. Since, the proposed buildability evaluation used a weighting system to indicate the difficulty embedded in some of the buildability factors, it is expected that the users/evaluators understand the project being evaluated, the buildability concepts and the various buildability improvements, as described in Chapter 2 and 7. Several piece of information will be required from the users/evaluators when CONPLAN performs the evaluation.

To start the buildability evaluation, the users/evaluators have to return to the main menu of CONPLAN as shown in Figure 9.22. When the users/valuators click on the button 'Show buildability analysis', a new interface will appear which contains a line plot image, transcript box, several functional buttons such as 'Check Buildability factors', 'Produce Element Graph Analysis', 'Show Element Report', 'OK' and several check boxes. The virtual reality tool has to be loaded after the evaluation has completed to show the building elements. Figure 9.25 shows the window interface of the buildability evaluation in CONPLAN.

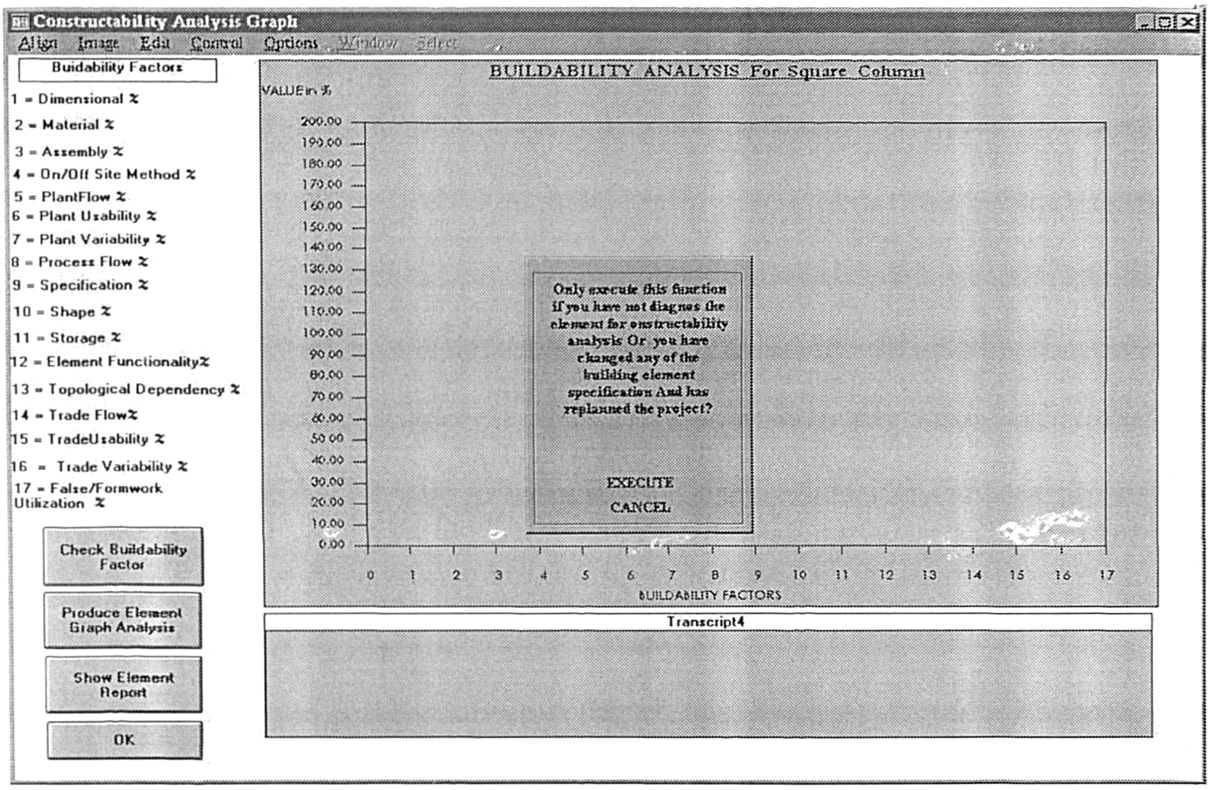


Figure 9.25 The buildability evaluation interface.

The line plot image in this interface is used by CONPLAN to display the buildability values of building elements derived from the evaluation approach. The Y Axis represents the scale of the buildability value, while the

X Axis represents the buildability factors that will be evaluated. The numbers on the X Axis is correspond to the buildability factors on the left hand side of the line plot image, i.e. 1 refers to Dimensional %, 2 refers to Material %, etc.

When the evaluation is completed, several line legends will appear at the bottom of the line plot image. This legend represents the buildability index obtained from each line plot. The transcript image which is situated below the line plot image is used by CONPLAN to display the textual report of the evaluation. It contains information about the building elements cost, their duration, and the total number of the elements which share similar properties. Below the description of the buildability factors, there are four buttons which are designed to be used subsequently by the users/evaluators to complete the evaluation process, e.g. 'Check Buildability Factors', 'Produce Element Graph Analysis', 'Show Element Report' and 'OK'.

The 'Check Buildability Factor' button is the main button which will execute the buildability evaluation processes of CONPLAN. When users/evaluators click on this button, a post message will appear on the screen. It contains initial instructions to the users/evaluators, that the buildability evaluation can only be performed if the evaluation has not been performed earlier, or a revised construction plan has been developed, if any of the building element specifications had been changed. The instruction is highlighted to avoid CONPLAN proceeding the buildability evaluation using incorrect information (see Figure 9.25). When the users/evaluators select to

'EXECUTE' this function, the buildability evaluation will proceed and several post input forms will appear on the screen to obtain further information from users/evaluators about the construction of the project. The first post input form will ask the users/evaluators to give a weighting value for ease of assembly to two types of formwork, i.e. traditional and standard. In this case, the traditional type means that the formwork is made up of timber, which needs to be measured and cut accordingly to fit a particular purpose of construction. While the standard formwork refers to a proprietary formwork which is purposely designed to be easy and flexible to use for the construction. Figure 9.26 depicts the weighting input form for highlighting ease of assembly for traditional and standard formwork.

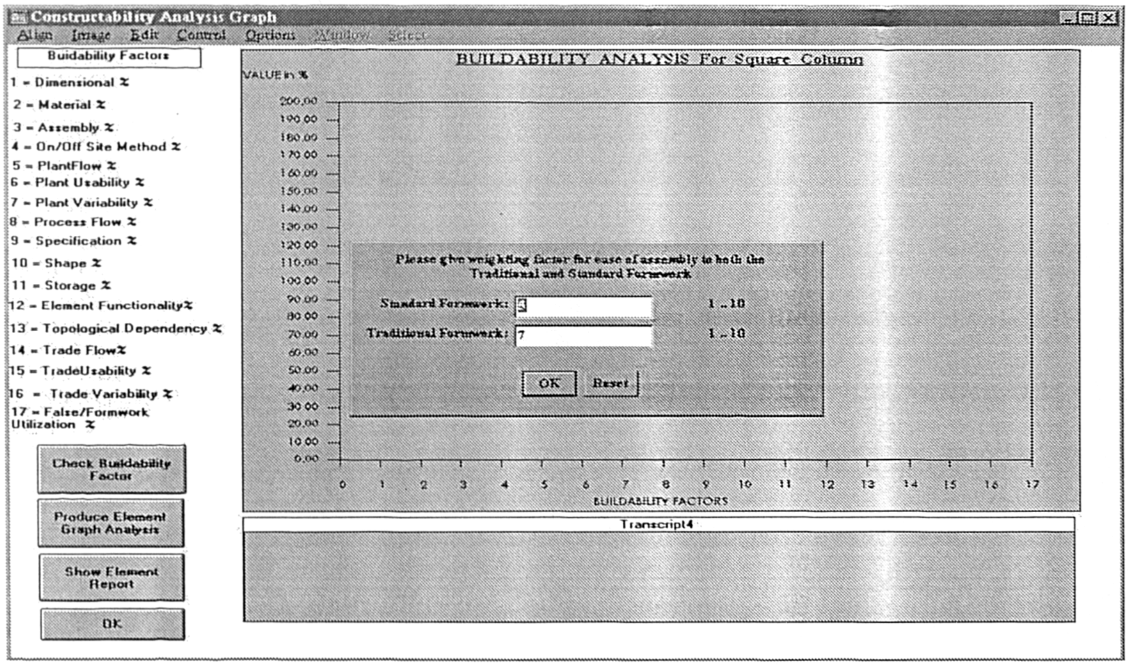


Figure 9.26. The post input form for determine the weighting value for the formwork.

The second post input form will ask the users/evaluators to give the storage weighting value for the formwork/falsework, scaffolds and materials on site. The weighting value in this case is used to highlight the amount of site space that the construction material and facilities will occupy (see Figure 9.26). CONPLAN will further ask the users/evaluators to identify the type of formwork used in the construction which either could be traditional or standard.

This answer will be used by the evaluation system to calculate the value of buildability when using these different types of formwork. The next input required by CONPLAN is about the method of construction selected for the building elements. Several main elements will be highlighted which require the answer from the users/evaluators as to whether it will be constructed onsite or off site, such as wall, beam, floor, column, door and window (see Figure 9.27).

Once this information has been filled, another post input form will appear which requires the users/evaluators to indicate the weighting value for different types of topological relationships which will normally be used in describing the building elements relationship, such as 'supported by', 'embedded in' and 'attached to'.

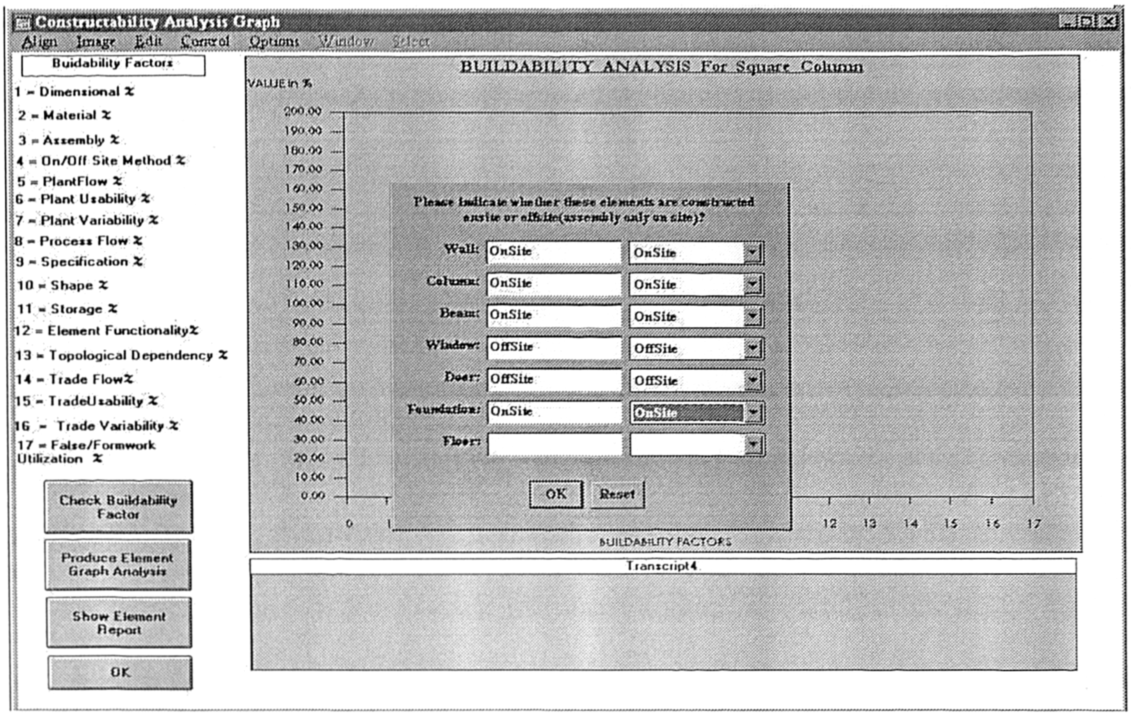


Figure 9.27 The users/evaluators input form for deciding the likely method of construction for the main elements.

The weighting value given to these topological relationships will indicate how strongly dependent a building element is to another element. Finally another post input form will appear on the screen which asks the users/evaluators to give a weighting value for two different types of construction methods, i.e. the wet process and the dry process.

Once all these inputs have been provided by the users/evaluators, CONPLAN diagnoses all the building elements objects and its construction activities to establish the buildability values. When the evaluation is completed, the users/evaluators can view the result from the graph, the text report and the virtual reality tool. A list of building elements to be selected will appear from a combo box. By selecting any of the elements represented, CONPLAN will search for their evaluated buildability values and display on the line graph.

A report can be viewed by clicking on the 'Produce Element Graph Analysis'. The number of the lines which will be displayed depends on the range of buildability indexes evaluated from the building element. If many lines appear on the graph, it indicates that this group of building elements has many different specifications which led to a variety of buildability indexes. Only six lines can be displayed in the graph. Each line is represented with a legend (displays at the bottom of the line graph) and attached to a total figure of the element's buildability index. Figure 9.28 depicts the result of the buildability evaluation represented on the line graph. A report on the evaluated building elements can be found when the users/evaluators click on the 'Show Element Report'. The report summaries the effect imposed by the building element, the cost to build each of the elements, the duration required, and the number of element types which share similar properties.

At the bottom of the report there are several check boxes assigned with a figure. These figures represent the legend of the line graph. The check boxes are used to highlight the evaluated building elements in a virtual reality tool. Users/evaluators have to open the virtual reality tool and used the

CONVERT sub menu (type 'k' on the virtual reality tool menu) to load the building model in order to use these check boxes.

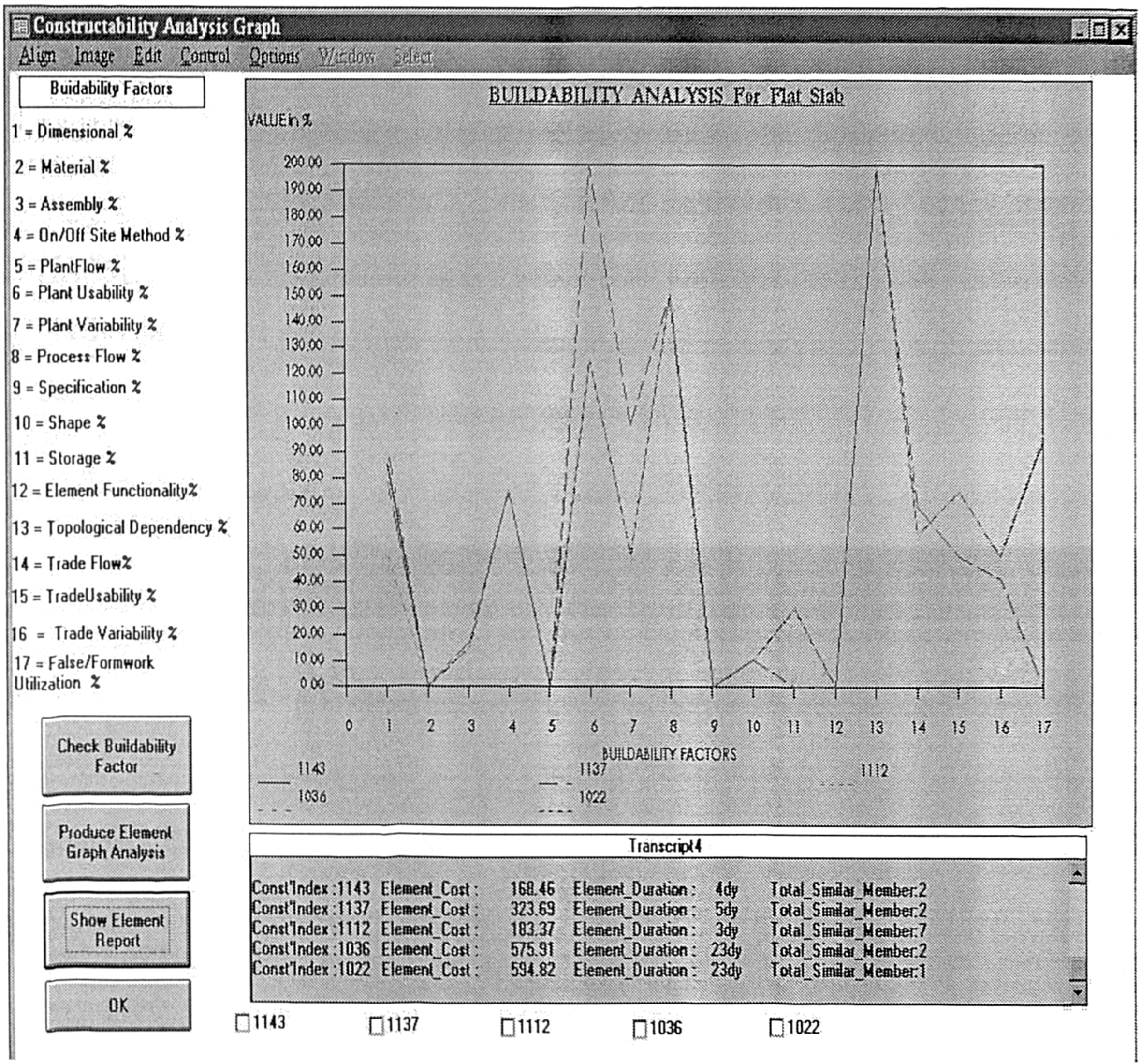


Figure 9.28 The lines graph for buildability score and index.

When the building model is loaded in the virtual reality tool, by clicking on the check box, the users/evaluators can view the evaluated building elements. Each check box represents the buildability value for a group of building elements. A higher value in the graph generally represents a greater difficulty of construction. Users/evaluators can study these lines and identify which factors impose greater influence on the buildability of the element. From Figure 9.28, a buildability evaluation result on flab slab is illustrated. The blue line has the highest score of the buildability index. The buildability factors which greatly influence the buildability of the elements are the plant usability and the topological relationship. By clicking on the check box which has a blue line buildability index, the building elements will be displayed on the virtual reality Figure 9.29.

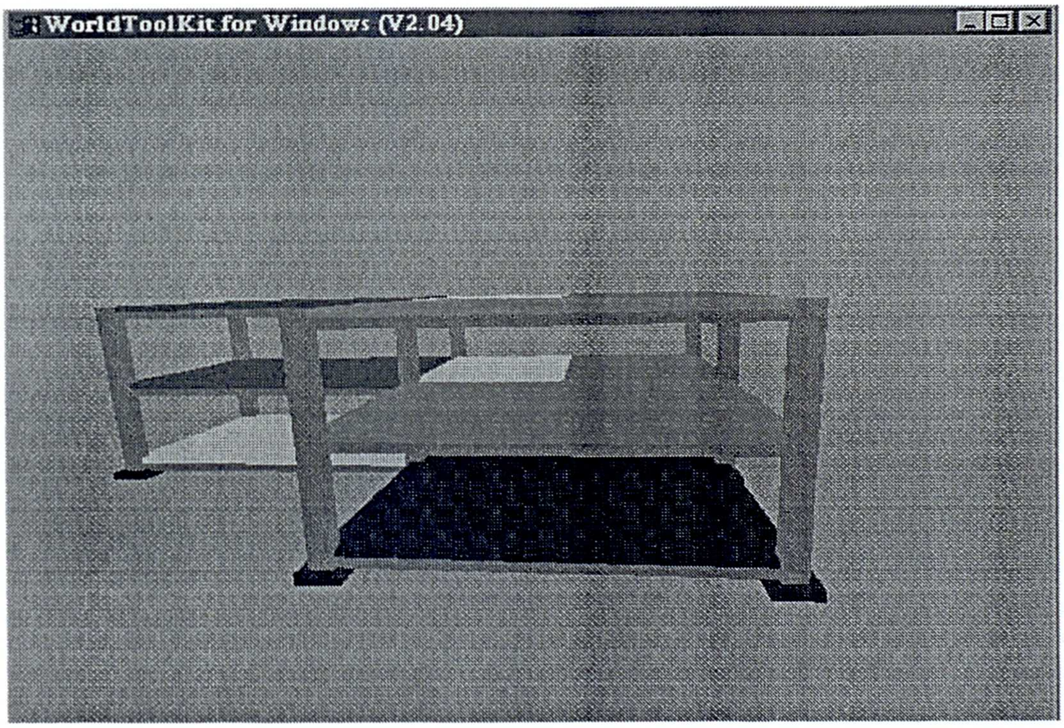


Figure 9.29 Displaying the selected building elements in VR.

9.7 Summary

This chapter has oulined an overview of the implementation process of CONPLAN as part of SPACE computer system environment. It highlights CONPLAN aims, its system architecture, its knowledge structure, its knowledge representation and its knowledge processing involved for generating the construction plan and buildability evaluation reports. A brief description for running the prototype is described and the results are also presented. The succeeding chapter will describe the experiments performed on CONPLAN within the integrated system.

Chapter 10
Experimenting with the prototype

10.1 Introduction

In chapter 9, the implementation of the integrated knowledge based system was discussed. It was also concluded in chapter 4, that buildability improvements can be implemented before actual construction starts on site, if an evaluation approach which can evaluate the design based on construction information is available to the designers. Both the construction plan and the buildability evaluation which contains the project specific construction information can be used to help designers to predict the scale of difficulty of the construction process associated with the design.

This chapter highlights the procedure of experimenting with the prototype and the validation results from the users/evaluators on the approach, applicability, and usefulness of the prototype.

10.2 The experimental approach

The aim of the experiment conducted on the prototype was to validate the approach, applicability and usefulness of CONPLAN in an integrated computer environment (SPACE) and providing recommendations for future approaches of the system implementations.

In the construction project, experimental research can be carried out based on two approaches (Kahkonen 1993):

1. an experiment which is based on data extracted from a running project on site.
2. an experimental study performed in a research laboratory based on the data from a finished construction project or one based on fictitious project data.

For this study the experiment was conducted using data from a completed construction project. The testing on CONPLAN was performed in two stages. The first stage was arranged to analyse the process of generating the construction plan and the second stage was to evaluate the process of buildability evaluation. To obtain the experimental feedback on CONPLAN in a wider scope, several construction practitioners, academics and researchers, were invited to test the system. Below are the processes of experimenting the prototype.

10.3 General arrangements and procedures of the experiment

The experiment with CONPLAN was performed on a two-storey reinforced concrete office building. Since CONPLAN is part of the SPACE prototype, the design information was fed into SPACE through AutoCAD/AEC and interpreted by the CAPE application which populate the building data module in the central core. The specifications of the building elements were determined concurrently from the specification data module. The design information was then used by CONPLAN to generate the construction plan and buildability evaluation, where the process of generating the construction plan were evaluated.

10.3.1 Experimenting with the construction planning process

Below are several suggestions made by the users/evaluators regarding the approach of and processes used in CONPLAN.

- Level of detail of planning information

The majority of the users/evaluators commented on the speed and level of planning detail provided by CONPLAN. The facilities provided by CONPLAN which can generate different levels of construction plans i.e. strategic, managerial, detail construction plan, were found to be acceptable by the users/evaluators. Although most of them appreciated the speed and level of planning detail produced by the system, the users/evaluators however, criticised whether the detailed construction plan is feasible for following on site. Nevertheless, as the approach demands to present a unit of activity with its construction resources to facilitate the buildability evaluation process and to meet the integration requirements, the usability and the approach are justified.

Some users/evaluators were concerned about the method used to aggregate the activities. It was agreed that a system which can decompose a high level construction activity until it represents a single unit of construction activity can provide an accurate representation of the plan. It is considered that the middle-top down and bottom up approach used by CONPLAN to decompose and recompose the construction activities can provide consistent representation of a construction plan.

Since it takes considerable time for construction planners to produce the same level of a detail of construction plan as that of CONPLAN, it was suggested that the approach and the automation facility provided by the system can assist the construction planner in providing quicker and detailed construction plans. However, it was also commented that, due to large amounts of information generated by CONPLAN, it would only be feasible to update and check the correctness of the plan, if the process is assisted by an updating and criticising facility.

- Allocation of construction resources

When allocating the construction methods and resources, CONPLAN assumed that the construction methods and the available resources which would be employed in the system were already decided collectively from other project participants. Most of the users/evaluators suggested that an input interface should be provided by the system to allow the user to select the various options of the available construction. Each option should have the facility to highlight the cost, plant, skilled labour and the likely duration required by each to perform a particular type of a construction activity. This facility was found to be essential to provide flexibility to users/evaluators for allocating the construction methods and carry out the 'what if' scenario. It was also suggested by the users/evaluators that the construction method used in CONPLAN should be expanded to give wider choices.

- Developing activities dependency

The users/evaluators found the decisions employed by the knowledge base for developing the activity dependencies were very useful. They all agreed that this could provide major advantages for construction planners in developing a speedy construction plan, since all types of dependency factors are considered. It was commented that the automation of the dependency decision can overcome the problems caused by insufficient representation of activity dependencies within current project networks.

However, several suggestions were made that it would be better for the users/evaluators to have some control on deciding the activity dependencies. Some of the user/evaluators would also prefer the system to highlight reasons and type of dependencies associated with the activities and allow users/evaluators to make changes if required during the process.

Nevertheless, the suggestions were discussed and two problems were anticipated if the users/evaluators were given the choice to alter the dependency suggested for the construction activities. Firstly, the process would become cumbersome since every single decision would require user/evaluators intervention. Secondly, the process of generating the construction plan would consume a longer time to develop.

Other users/evaluators prefer that the activity dependencies decision is automatically made by the system, but like to have some control to change the established dependency after the plan has completed. The users/evaluators also suggested that the changes made on the completed plan should be recorded in the knowledge base for future comparison.

- Creating the construction plan

Most users/evaluators were satisfied with the adapted approach and realised the advantages of automating the process through the use of the knowledge bases. The speed of generating the construction plan can help construction planners to speed up the planning preparations and can encourage the development of alternative plans. Nevertheless, some comments were made on the slow process of importing data from the project management software i.e. after the plan has been determined. This is mainly contributed by the limitation of the software packages (KAPPA and CA-SuperProject).

- Construction simulation in VR

The construction simulation shown in VR was considered as a very useful tool to planners where the correctness and approachability of the plan can be easily evaluated. It can also be a useful presentation tool to impress clients and update the management on the progress of work at the site. A suggestion was also made that, the construction simulation would be more realistic if it could simulate the movement of materials, plant and facilities used on construction. This process is addressed by the site layout planning application in the SPACE environment.

10.3.2 Experimenting with the buildability evaluation process

In the second stages of the experiment, the buildability evaluations were carried out. Explanations were given earlier to the users/evaluators on the aims of the evaluation which were set to highlight buildability factors on the design solution. The evaluation was not designed to criticise the design solution but to emphasise the expected buildability problems based on the general principles of buildability improvements. The users/evaluators found the demonstration acceptable, however, several comments were made.

- The measurements approach using the buildability scores and index

Having considered the factors and scope of buildability, it was felt by the users/evaluators that, as a prototype application, the measurements used were sufficient to help identify prominent buildability factors on design which later could have considerable effects on construction. The users/evaluators found the approach applied to evaluate general buildability factors such as repetitiveness, standardisation, ease of assembly through topological relationships, trade flow, plant flow, process flow, etc., to be very useful and practical. It was felt that the automation and integration approach of the evaluation provided by CONPLAN would not be feasible, if it were to be performed manually.

- The allocation of weighting in the evaluation

The allocation of weighting to the buildability factors were the main concern of most users/evaluators. It was established that the weighting would vary between users/evaluators. Suggestions were made that, since the allocation of the weighting is a subjective matter depending on the experiences of users/evaluators, more explanation of the facilities should be provided to assist the users/evaluators to decide the weighting i.e. by explaining the scale to a more readable format such as those between difficulty and ease, less important to important, etc. The users/evaluators also agreed that since some of the measured buildability factors were intangible e.g. dry and wet process, the weighting allocation system is a practical approach.

- The graph, textual report and visualisation in VR

The range of reports produced by the system which highlights the factors of buildability, cost, duration, and visualisation for each type of building element were found to be acceptable by the users/evaluators. The majority of the users/evaluators agreed that the produced format of the reports could effectively help users/evaluators to evaluate their design. It was also agreed that CONPLAN can be a very useful tool to assist designers to check their design solutions against the unforeseeable buildability problems. Suggestions were made that the produced report can be more effective, if explanations are given when users/evaluators highlight the various line graphs derived from the evaluation.

10.4 Overall conclusion of the experiment

CONPLAN was developed to prove that a systematic buildability evaluation can be developed from project specific construction planning information, if it is made available to the users/evaluators. The feature of CONPLAN as an integrated application in SPACE, demonstrates that this can be carried out in practice and that the capabilities of the developed information models and the modularised integrated approach is very effective. The combination of knowledge based system, databases, project management and virtual reality software, showed to be effective tools for quickly generating the information required for the construction plan and to support the buildability evaluation.

However, several suggestions were highlighted by the users/evaluators in order to improve the general capabilities of the system i.e. the knowledge base system and the user interface. Among the suggestions proposed are:-

- Allowing users/evaluators to have control on changing the construction plan.
- Allowing users/evaluators to decide the various options of construction methods from a database.
- Allowing users/evaluators to define the group representing the construction activities.
- Extending the database of construction plant specifications and facilities
- Integrating with other specific plant and facilities selection system in order to assist the construction planning process and deciding the right construction methods.

- Provide an automatic checking and explanation on the correctness of defining the activities dependency if users/evaluators made any changes to the plan.
- Provide automatic facilities which ask users/evaluators to decide to overwrite any changes made and saving previous construction plans with different versions.
- Provide detail explanations or comparison facilities for each of the line graphs produced from the evaluation when the user highlights the line on the screen.

10.5 Summary

This chapter has highlighted the result of experimenting the approach and applicability of CONPLAN for generating the construction plan and buildability evaluation on an integrated system environment. Several key processes were tested and several comments and suggestions were put forward for future improvement and development of the prototype. The following chapter will conclude the study and provide the research recommendations for the construction industry.

Chapter 11
Summary and conclusions

11.1 Introduction

The study aimed at bringing the design and construction process together by formalising the construction planning process to enable the exchanging of information through computer integrated environment. This research has described the aspects and use of the construction planning processes to support various applications in a project life cycle. the integration of information, buildability in construction, and the formalisation of construction information for buildability evaluation.

The integration of construction planning domain as part of a fully integrated project data model can also support various other applications such as buildability evaluation, estimating, site layout planning, material management, project control, monthly valuation, etc. This chapter summarises the main stages of this study and outlines its main conclusions.

11.2 Summary of the research work

This study was initiated by the lack of immediate and systematic feedback of project construction specific information to assist designers to examine the impact of their design on construction before the actual construction starts on site. The lack of integration between design and other construction processes such as construction planning, estimating, buildability evaluation, site layout evaluation, etc. has significantly contributed to the fragmentation of the industry. This has created various problems during the construction stage especially those which are related to buildability. Construction information is therefore essential, at the design stage, to enable the designers to examine their design on construction and to evaluate the various buildability problems.

Previous research in this field has revealed that the current development of an integrated computer environment to support the requirements of information exchange over the project life cycle are practically hindered by the fact that ;

- Design and construction is separated by the professions, performed in a sequential manner and subjected to different procurement systems. Each of the project participants has their own views of information which is influenced by their area of discipline.

- The growing complexity in design, construction, building materials, etc. and volatility of the industry at micro and macro levels, continuously increase the needs for integration.

- The scope and the scale of information exchange requirements in the construction industry are enormous which could be contributed from as early as the briefing stage to design, construction, maintenance and demolition.

- The production of project specific construction information (i.e. construction activities, construction methods. resources, construction duration and cost) could not be implemented efficiently unless it is developed using a project data model (product and process models) as a central core in an integrated computer environment.

Research on buildability has disclosed that the buildability problems can vary between projects, as well as between stages of a project. It can also be influenced by the procurement system and the sequence of the project development. Various generic principles for buildability improvements and evaluation have been produced by numerous studies such as repetitiveness, standardisation, ease of assembly, dimensional tolerance, etc. It was also unveiled that the lack of buildability consideration in design solutions, was contributed by the absence of project specific construction information to designers during the design stage.

Most of the project construction information which is required by designers, is available in the project construction plan. This plan is a formal document which is used by the constructor to outline and control the various construction activities and their associated resources. It reflects the decisions taken by the constructor to realise the design solution based on the design specifications, the site environment, safety and regulations, and the availability of resources. The construction plan is also a major document which is normally used to support other construction applications such as estimating, monthly valuation, site layout planning, resources management, etc. Therefore, the construction planning process is considered to be vital to bridge the knowledge gap between design and construction.

The main aims of this study are to formalise the construction planning process in order to support the exchange of information between design and construction processes in an integrated environment. The integration enables project construction information and buildability evaluation, to be performed in an integrated manner.

The requirements for identifying appropriate data and process models. led to a full information analysis of the construction planning and buildability domains. An object oriented analysis methodology (Martin,1993) has been adopted for this purpose where information models which highlight the static and dynamic aspect of these domains have been developed. The construction planning and buildability evaluation processes were modelled using object flow diagrams. The modelling process has been carried out with the aim of allowing full integration with other construction disciplines such as construction planning, estimating, site planning, etc. Object relationship diagrams were also produced to outline the static properties of the objects involved in both the construction planning and the buildability evaluation domains.

The major processes involved in the construction planning have been identified such as gathering project information, defining construction activities, selecting construction methods, sequencing the construction activities, resource allocating and optimising the construction plan. The main objects have also been identified in this process such as construction plan, construction activities, construction resources, construction methods, construction options, dependency factors, and the site layout plan. A top down and bottom up approach is followed to develop the necessary mechanism to generate the construction plan. For buildability, eleven major processes and several evaluation objects have been outlined. Each of these processes use different types of construction and design information.

These models have then been mapped into an object oriented knowledge base environment (KAPPA-PC^{TM}) as part of an integrated computer environment SPACE (Simultaneous Prototyping for An integrated Construction Environment). This led to the development of CONPLAN (intelligent

CONstruction PLANning generator for design rationalisation). Full data sharing and exchange has been achieved between design, estimating, site layout planning, and construction planning. The data provided by such applications in SPACE are essential for CONPLAN to generate the construction plan and buildability evaluation. CONPLAN is able to assist the users/evaluators to automate the process of construction planning which generate the project specific construction information and the buildability evaluation.

The implementation of CONPLAN in an integrated construction environment has enabled the research to achieve its aims and objectives as well as to validate the developed information models. CONPLAN, as a prototype, has successfully provided an integrated computer assisted tool to users/evaluators for generating construction plans, and supporting buildability evaluation, over a project life cycle.

11.3 Main conclusions

The main conclusions of this study are:-

1. Previous research on construction planning highlighted that the construction information is important to the various stages of the project life cycle. Since other project participants e.g. estimator, site planner, resources manager, surveyors, etc., depend on the construction planning

information to fulfil their requirements, the fomalisation of construction planning is therefore essential for the integration between these parties.

2. A study on the construction planning process highlighted that it requires an integrated approach for information exchange. The approach is essential to support the various planning processes such as gathering project information, defining construction activities, allocating the construction methods, sequencing the construction activities, etc. throughout the construction stages. Therefore the output of the construction planning process is determined by its planning approach i.e. quality, availability, capability of exchanging the design and construction data within the construction environment.

3. The integration of construction planning with other construction disciplines requires the identification of information needed to be exchanged between other project participants. This identification enables the integrated application to interrogate and use the design and construction information as and when required. Several major requirements have been identified to support the integration e.g. the data and process models to represent the various stages of a project life cycle, a structural framework to support data management and integration, a modelling methodology and implementation tools.

4. Previous research in the construction planning revealed that much of the integration was performed as a direct link between various applications using the available software packages (i.e. construction planning and estimating, construction planning and resources management, etc.). The integration of construction planning with other disciplines using the product and process models are hindered by the complexity of modelling the interactions involved amount project participants over the project life cycle, unavailability of a common standard for data exchange and lack of integration framework for supporting the multiple views in a project life cycle.

5. Automating the construction planning domain requires the identification and evaluation of its processes and their relevant information requirements. Many of these processes can be performed efficiently with the assistance of computer technology i.e. defining construction activity, defining activity dependency, calculating activity duration and cost, defining the resources required, establishing project duration and cost, criticising construction activity plans, establishing delays and replanning. For other processes such as resource allocation and optimisation, and optimisation of the construction plan, which require various evaluation criteria and complex decision making processes, it is more effective to let the construction planner carry out such processes.

6. It is a normal practice that designers use previous design experience to incorporate buildability improvements in their design solutions. However, since each design and construction has unique features, and as it is performed and constructed by different organisations, using different materials, disciplinary skills and location, the need for immediate and systematic buildability evaluation based on project specific construction information is essential if building performance is to be improved. Little progress has been made to provide a general evaluation system which can measure the influence of buildability before actual construction work proceeds on site. As an integrated application, CONPLAN has produced a generic approach for buildability evaluation which uses the improvement principles of buildability to evaluate the design.

7. This study has proven that by capturing the project construction specific information from an integrated construction planning process, a buildability evaluation can be performed on the design solution. The development of a detail construction plan from the integrated approach, along with the availability of the design information has enabled the buildability evaluation to be developed. Buildability measurements have been established to assist designers to identify buildability problems in the design solution.

8. Object oriented methodology has proved to facilitate the identification of complex information involved in the construction planning and

buildability evaluation. Such a methodology allows different information requirements, from different project participants to be incorporated within their own perspectives, thus eliminating the need to make compromises. The ability to use the same information in different ways in more than one model for multiple disciplines, is the essence of the object oriented paradigms.

9. The implementation of object oriented models for construction planning and the buildability evaluation in an object oriented knowledge based system, within an integrated computer environment has proved to be essential for bridging the knowledge gap between design and construction processes. The implementation of CONPLAN as part of integrated computer environment SPACE, has demonstrated the ability and usefulness of the system to overcome the inefficiency of information exchange between design and construction.

10. The proposed concept of the objects life cycle used in SPACE implementation, within the modularised project model in the integrated construction environment, provides an effective tool to satisfy the multiple views needed for information sharing and exchange. A "View Moderator" which consists of a dynamic collection of methods stored in the concerned application data modules in SPACE, enables the integration to be carried out effectively and efficiently.

11. The implementation of a virtual reality tool to simulate the generated construction plan significantly enhances the construction planning process and buildability evaluation results. The visualisation facility provides greater understanding and awareness of the construction plan and the buildability evaluation to the project management team, since the simulation of the construction process at an early stage can contribute to the reduction of construction rework. The simulation of the construction sequence can also effectively identify what should be constructed in the coming period.

11.4 Recommendations for future work

The scope and the approach adopted in this study only focused on a small area of integration between design and construction (i.e. construction planning and buildability evaluation). Although the study has proven that the integration of information generated from the construction planning process is useful to support the project life cycle, there are many more areas in this domain which need to be researched, enhanced and extended, to obtain more reliable feedback.

The main recommendations and future research areas which can be investigated to improve the use of the construction planning process and buildability evaluation on the design solution are ;

1. Further study would be required to define other physical relationships between designed objects. The correct definition of topological relationships between building elements and other elements in the project would increase the accuracy of determining the construction activities dependency, as well as the buildability evaluation.

2. Other knowledge based systems, e.g. selecting a particular construction plant, construction methods, etc., should be incorporated in a construction planning process. This pre-selection facility which can be based on the cost, time and physical aspects (site, and building) of the project would improve the overall efficiency of the project management functions.

3. The construction planning domain can be extended into project control where input from site would be evaluated in order to update the construction plan. This part of construction planning would require modelling on event objects involved in the process. This future research enables the information on the progress of work on site to be exchanged between other parties in the construction process to keep them up to date with the information on the running project.

4. The development and use of a weighting system, which was incorporated in CONPLAN buildability evaluation, needs further research and observation in order to establish a formalised approach to determining

the associated weighting factors. This approach will improve consistency among users/evaluators of this system.

11.5 Recommendations for the industry

1. The research has developed the information models required for developing construction plans and buildability evaluation. It has also identified the information requirements in the concerning develoment of construction plan and buildability evaluation. The proposed models can be used by the construction industry to enhance integration which could be used to reflect the long term objectives of the company or industry.

2. The development of CONPLAN as a prototype in an integrated system environment has facilitated the generation of construction planning and buildability evaluation for designers. The approach has demonstrated the feasibility and applicability of integrating CONPLAN as part of the design evaluation process. It is important that the industry starts now with some experimentation using CONPLAN and SPACE to improve efficiency and performance in project development.

3. The framework of integration in SPACE can be utilised by the industry to develop a Computer Integrated Construction (CIC) if the strategic integration of information between design and construction is identified for the company or industry. The adoptation of SPACE methodology

can effectively and efficiently improve system integration and project development.

4. To improve the information modelling process of the project life cycle, the object oriented paradigm is recommended to be used as a standard approach in the construction industry.

REFERENCES

Abudayyeh, O.Y., Rasdorf, W.J.(1991), Integrated Cost and Schedule Control Automation, Preparing for Construction in the 21st Century, Proceeding of Construction Progress 1991, ASCE, New York, pp. 679-686.

Ackoff, R.L.(1970), A Concept of Corporate Planning, John Wiley and Sons. Inc., New York.

Adam, S. (1989), Practical Buildability, CIRIA, Butterworths, London.

Ahmed, S., Sriram, D, Logcher, D.(1991), A Comparison of Object Oriented Database management Systems for Engineering Application, Proceedings. Seventh ASCE Conference on Computing in Civil Engineering and Symposium on Databases, Washington D. C, May, pp.588-597.

Ahuja, H. N., Dozzi, S. P., Abourizk. S.M.(1994), Project Management. Techniques In Planning and Controlling Construction Projects, 2nd ed., John Wiley & Sons, Inc.

Allsopp, K. (1983), Buildability : An Architects View, architects Journal . Vol. 177(4), pp. 29.

Alkass, S., Moselhi, O., Abdou, A. (1991), An Integrated System to Aid Design Engineers in Selecting Easy to Construct Detail Design, Artificial Intelligence and Civil Engineering, Civil-Comp Press, pp. 169-175.

Alshawi, M. (1989), The Potential of Object Oriented Programming For The Development of Expert System in Construction Industry, Artificial Intelligence, Civil-Comp, London, pp. 27-32.

Alshawi, M. (1995), Object Definition and The Life Cycle of Objects, CIB Workshop on Computers and Information in Construction, Stanford University, California, pp. 361-369.

Alshawi, M. and Che Wan Putra, F. (1995), Object Definition In An Integrated Environment, Civil-Comp 95, London, August, pp.87-92.

Alshawi, M., Faraj, I. (1995), Integrating CAD and Virtual Reality in Construction, Proceeding of a Conference on Virtual Reality and Rapid Prototyping for Engineering, Salford, pp. 78-85.

Alshawi, M., Sulaiman, M. J. (1995), Applying Structured Process Analysis to Site Layout Planning, Proceedings of the Sixth International Conference on Computing in Civil and Building Engineering, Berlin, Germany, pp. 477-483.

Alshawi, M., Jagger, D. (1991), An Expert System To Assist in Generating and Scheduling Construction Activities, Computer & Structures, Vol. 40(1), pp. 53-58.

Alshawi, M., Jagger, M.D., Brandon, P. S. (1990), An Expert System To Assist in Generating and Scheduling Construction Activities, Proceeding CIB 90, Building Economics and Construction Management, Vol. 2, pp. 375-384.

Alshawi, M., Hassan, Z. (1994), A Run Time Generation of Construction Plans: Integrating Construction Information Model With Building Model. , Proceedings of ECPPM'94, Dresden/Germany, October 5-7, pp. 303-308.

Alshawi, M., Hassan, Z. (1997), Buildability Analysis in an Integrated Computer Environment, Submitted for International Conference Rehabilitation and Development of Civil Engineering Infrastructure Systems, Beirut Lebanon.

Alshawi, M., Underwood, J. (1996), Applying Object Oriented Analysis to The Integration of Design and Construction, Automation in Construction, Vol. 5(2), pp. 105-120.

Alshawi, M., Underwood, J. (1996), Project Estimate and Monthly Interim Valuation Certificates Generation In An Integrated Construction Environment, Intermediate Report for An EPSRC and Taylor Woodrow Funded Research Project, University of Salford.

Alshawi, M. (1989), The Potential of Object Oriented Programming For The Development of Expert System in Construction Industry, Artificial Intelligent, Civil-Comp, London, pp. 27-32.

Aouad, G.(1991), Integrated Construction Planning System for the Construction Industry., PhD thesis, Loughborough University.

Aouad, G., Betts, M., Brandon, P., Brown, F., Child, T., Cooper, G., Ford, S., Kirkham, K., Oxman, R., Sarshar, M., Young, B. (1994), Integration of Construction Information (ICON) Final Report- Integrated Database for Design, Procurement and Management of Construction., Department of Surveying & Information Technology Institute, University of Salford, July.

Aouad, G., Ford, S., Brandon, P., Brown, F., Child, T., Cooper, G., Kirkham, K., Oxman, R., Young, B. (1993), Information Modelling In Construction Industry: The Information Engineering Approach, Construction Management And Economics, No. 11, pp. 383-397.

Arditi, D. (1983), Diffusion of network planning in construction, Journal of Construction Engineering Management, Vol.109(1), pp.1-12.

Augenbroe, G. (1994), An Overview of The COMBINE Project, Proceedings of ECPPM, Dresden/Germany, pp.547-554.

Augenbroe, G.(1995), The COMBINE Project: A Global Assessment. CIB W78 Workshop on Computers And Information in Construction, August, pp.163-171.

Banwell, H. (1964), The Placing and Management of Contracts for Building and Civil Engineering Work, HMSO.

Baxter, A. (1983), Buildability : A Structural Engineer's View, Architects' Journal, Vol.177(5), pp. 30.

Bennett, J.(1985), Construction Project Management., Butterworths.

Bennett, J., Ormerod, R.N. (1984), Construction Project Simulator. Final Report of SERC Research Grant, Department of Construction Management, University of Reading.

Benjamin, C.O., Babcock, D.L.. Yunus, N.B., Kincaid, J. (1990), Knowledge-Based Prototype for Improving Scheduling Productivity, Journal of Computing In Civil Engineering ASCE, Vol. 4(2), pp.124-133.

Betts, M ., Fisher, M., Koskela, L. (1993). The Purpose and Definition of Integration, Integration of Construction Information N + N, Science and Engineering Research Committee, May.

Beynon-Davies, P. (1991), Expert Database Systems, The McGraw-Hill Book Company.

Birtwistle, G.M. (1979), Discrete Event Modeling on SIMULA., London, MacMillan.

Bjork, B.C. (1992), A Unified Approach for Modeling Construction Information, Building and Environment, 27, pp. 173-194.

Bjork, B. C. (1992), The Topology of Space , Space Boundary and Enclosing Structures in Building Product Data Models, CIB W78 Workshop on Computer Integrated Construction, Montreal, Canada, May, pp. 56-92.

Bowley, M. (1966), The British Industry, Cambridge University Press.

Booch, G. (1994), Object Oriented Analysis and Design with Applications, The Benjamin-Cummings, Inc, New York.

Carrara, G., Kalay, Y.E., Novembri, G. (1991), Computational Framework for Supporting Creative Architectural Design, Evaluating and Predicting Design Performance, Kalay, Y.E.(ed.), A Wiley-Interscience Publication, pp.17-36.

Che Wan Putra, CWF. (1997), Object Definition and Data Exchange in Integrated Construction Environment, PhD Thesis (in preparation), University of Salford, United Kingdom.

Chen, P.(1976), the Entity-Relationship Model: Towards a Unified View of Data, ACM Transaction Databases Systems, Vol. 1(1), pp. 9-36.

Cherneff, J. (1988), Automatic Generation of Construction Schedules From Architectural Drawings, MSc. Thesis, M.I.T.

Cherneff, J., Logcher, R., Sriram, D. (1991), Integrating CAD with Construction Schedule Generation., Journal Of Computing in Civil Engineering, ASCE, Vol. 5(1), pp. 64-84.

Co-ordinated Project Information(CPI) (1987), Common Arrangement of Work Sections for Building Works a Guide With Examples, CPI.

Cooke, B.(1992), Contract Planning and Contractual Procedures, 3rd Edition, Macmillan, London.

Crawshaw, D. T. (1976), Working Drawings in Use, Department of Environment, London.

Cribbs, J., Moon, S., Roe, C. (1992), An Evaluation of Object Oriented Analysis and Design Methodologies., SIGS Books.

Coad, P., Yourdon, E. (1991), Object-Oriented Programming Analysis, Englewood Cliffs, NJ: Yourdon Press/Prentice-Hall.

Constructability Industry, (CII), USA (1986), Constructability: A Primer, Publication 3-1, Construction Industry Institute, University of Texas, Austin.

Construction Industry Research and Information Association, (CIRIA), UK, (1983), Buildability: An Assessment, A Special Publication (CIRIA), No 26.

Coombs, M. (1983), Buildability : A Delegate's View, Architects Journal, Vol. 177(5), April, pp.47.

Currie, K., Drabble, D. (1992), Knowledge-based Planning System: A Tour, International Journal of Project Management, Vol.10(3), pp. 131-136.

Darwiche, A., Levitt, R.E., Hayes-Roth, B. (1989), OARPLAN: Generating Project Plans By Reasoning about Objects, Actions and Resources., Artificial Intelligence For Engineering Design, Analysis and Manufacturing, 2(3).

Davis, E.W. (1974), CPM Use In Top 400 Construction Firm., Journal Construction Division, ASCE, 100(1), pp. 39-49.

Dermer, J.(1977), Management Planning and Control Systems, Irwin-Dorsey, Georgetown, Ontario.

DeMarco T.(1978), Structured Analysis and System Specification, Yourdon, New York.

Dunican, P.(1984), The UK Construction Industry, Computer Technology in Construction, Proceeding of a Conference Organised By The Institution of Civil Engineers (ICE), London 25-27 Sept, pp. 1-12.

Dym , C.L, Levitt, E. R. (1991), Knowledge Based Systems in Engineering, McGraw-Hill Inc., New York.

Eastman, C.M. (1991), Use of Data Modelling in the Conceptual Structuring of Design Problems, CAAD Futures 91, Schmitt, G. (ed.), pp. 225-244.

Eastman, C. M. (1993), Life Cycle Requirements for Building Product Models, Management of Information Technology for Construction, Mathur, K. et al.,(eds), World Scientific Publishing Co., Singapore, pp. 369-390.

Eastman, C.M. & Fereshetian, N. (1994), Information Models for Use In Product Design: A Comparison., Computer-Aided Design, Vol. 26(7), pp. 551-572.

Echeverry, D., Ibbs, W., Kim, S. (1991), Sequencing Knowledge for Construction Scheduling , Journal of Construction Engineering and Management, Vol.117(1), ASCE, pp.118-130.

Elzarka, H.M., Bell, L.C. (1995), Object - Oriented Materials Management System, Proceeding of The Second Congress on Computing in Civil Engineering, Mohsen, J.P. (ed.), ASCE, Vol.1, pp. 688-695.

Emmerson (1962), Survey of Problem Before the Construction Industry, (The Emmerson Report), HMSO, London.

Erskine-Murray, P. E.(1972), Construction Planning-Mainly a Question of How, Occasional Paper, No.2, The Institute of Building, England.

Euler, J. K.(1993), Construction Site Management Using Knowledge-Based 3D Animated CAD Models, A/E/C System Computer Solutions, May-June, pp. 7-14.

Ewen, I., Alshawi, M. (1993), An Object Oriented Approach For Interpreting Architectural CAD Drawings, Information Technology for civil & structural engineers, Topping, B.H.V., Khan, A.I. (ed.), Civil Comp Press (Proceedings), Edinburgh, pp.167-174.

Faniran, O.O., Oluwoye, J.O., Lenard, D.(1994), Effective Construction Planning, Construction Management and Economic, Vol. 12(6), pp. 485-499.

Faraj, I. Z. (1994), Verification and Machinability of Manufacturing Features in a Product Modelling Environment, Ph.D Thesis, Department of Mechanical Engineering, University of Leeds.

Fenves, G. L. (1989), Object Oriented Models for Engineering Data, Computing in Civil Engineering: Computer in Engineering Practice, Proceeding of Sixth Conference, ASCE, T.O., Barnwell Jr. (ed.), pp. 564-571.

Ferguson, I.(1989), Buildability In Practice, Mitchell's Professional Library, London.

Fiadeiro, J., Sernadas, S., Maibaum, T., Sernadas, A. (1992), Describing and Structuring Object for Conceptual Schema Development, In Conceptual Modeling Databases and Case, Loucopoulos, P., Zicari, R. (ed.), John Wiley & Sons, Inc., pp. 117-138.

Fisher, M. (1991), Reasoning about Constructability: Representing Construction Knowledge and Project Data, Artificial Intelligence and Structural Engineering, Civil-Comp Press, pp.105-112.

Fisher, M (1993), Automating Constructability Reasoning with a Geometrical and Topological Project Model, Computing Systems in Engineering, 4 (2-3), pp179-192.

Fisher, M., Aalami, F. (1994) , Model-based Constructability Analysis :The MOCA System., CIB W78 Workshop on Computer Integrated Construction, August, 1-9.

Fisher, M. A., Aalami, F. (1996), Scheduling With Computer-Interpretable Construction Method Models, Journal of Construction Engineering and Management, Vol.122(4), December.

Fisher, M., Luiten G.T., Aalami, F. (1995). Representing Project Information and Construction Method Knowledge for Computer-Aided Construction Management., CIB Workshop on Computer and Information In Construction, W78, August, pp. 404-403.

Ford, S., Aouad, G., Brandon, P., Brown, F., Child, T., Cooper. G.S., Kirkham, J.A., Oxman, R., Young, B. (1994), The Object Oriented Modelling of Building Design Concepts, Building and Environment, Vol. 29(4), pp. 411-429.

Froese, T., Jr. Paulson, B.C. (1994), OPIS: An Object Model-Based Project Information System, Microcomputers in Civil Engineering, No. 9, pp. 13-28.

Froese, T. (1993), Project Modeling and Data Standards for AEC, Proceeding of Fifth International Conference (V-ICCCBE), Computing in Civil and Building Engineering, Anaheim, California, USA, 1730

Froese, T. (1995), Core Process Models And Application Areas In Construction, CIB Workshop on Computers and Information in Construction, Stanford University, California, pp. 427-436.

Froese, T. (1995), Models for Construction Process Information, Proceeding of The Second Congress on Computing in Civil Engineering, Mohsen, J.P. (ed.), ASCE, pp. 5-12.

Galbraith, J.R.(1972), Organisation Design, An Information Processing View, In Organisation planning Cases and Concepts, R.D Irwin and Dorsey Press, Ontario.

Galle, P. (1995), Toward Integrated, Intelligent and Compliant Computer Modelling Of Buildings, Automation in Construction, Vol. 4(3), pp. 189-211.

Geddes, S. (1985), Estimating for Building and Civil Engineering Works, Eight Edition, Chrystal-Smith, G., Jolly, P.(ed), Butterworths.

Gillies, A.C. (1991), The Integration of Expert Systems into Mainstream Software (1st. ed.), Chapman & Hall Computing.

Gray, C.(1983), Buildability: The Construction Contribution, The Chartered Institute of Building, Occasional Paper No.29.

Gray, C.(1986), 'Intelligent' Construction Time and Cost Analysis, Construction Management and Economics, Vol. 4(2), pp. 135-150.

Griffith, A. (1995), Buildability: The Effect of Design and Management on Construction- A Case Study, Serc/Heriot-Watt University Publication.

Griffith, A. (1984), A Critical Investigation of Factors Influencing Buildability and Productivity, Ph.D. Thesis, Heriot-Watt University.

Griffith, A. (1986), Concept of Buildability, International Association of Bridge and Structural Engineering (Workshop) Conference, Zuerich, IABSE 53, pp. 105-116.

Hannus, M., Pietilдinen, K. (1995), Implementation Concerns of Process Modeling Tools, CIB W78 Workshop on Computers And Information in Construction, August, pp 449-458.

Hannus, M., Karstila, K., Tarandi, V. (1994), Requirements on Standardized Building Product Data Models, ECPPM 94, Product and Process Modeling in the Building Industry, Scherer, R.J. (ed.), October, pp.43-50.

Harris, F.C., Price, A.D.F., Emsley, M.W. (1985), An Evaluation of Production Output for Construction Labour and Plant, Department of Civil Engineering, University of Loughborough.

Harrison, F.L. (1981), Advanced Project Management, John Wiley and Sons, New York.

Hendrickson, C., Zozaya-Gorostiza, C., Rehak, D., Baracco-Miller, E., Lim, P. (1987), Expert System For Construction Planning, Journal of Computing in Civil Engineering, Vol. 1(4), pp. 253-269.

Hendrickson, C., Au, T. (1989), Project Management for Construction, Prentice Hall, Englewood Cliff, N.J.

Hendrickson, C., Maher, M. L. (1989), Issues in Computer Based Design/Construction Integration, Proceeding of Construction Congress, Excellence in the Constructed Project, ASCE, pp.129-136.

Hon, S.L., Gairns, D.A., Wilson, O.D. (1989), Buildability: A Review of Research and Practice, Australian Institute of Building Papers, Vol. 3, pp. 101-118.

Howard, H.C., Levitt, R.E., Paulson, B.C., Pohl, J.G., Tatum, C.B. (1989), Computer Integration: Reducing Fragmentation in AEC Industry, Journal of Computing in Civil Engineering, ASCE Vol. 3(1), pp.18-32.

Howard, H.C. (1991), Prototype Integrated Environment for AEC Data, Computing in Civil Engineering & Symposium on Databases. ACSE, pp.458-465.

Illingworth, J.R. (1984), Buildability, Concrete, August, pp. 10-11.

Illingworth, J.R.(1984), Buildability: Tomorrow's Need, Building Technology and Management, February, pp.16-19.

Illingworth, J.R.(1984), Concrete in Building: High Rise Capabilities, Building, January 20th, pp. 66-67.

Illingworth, J.R. (1993), Construction Methods and Planning, E & FN, Chapman & Hall, London,

Iosifidis, P., Tah, J.H.M., Howes, R. (1995), An Advanced Object Oriented Architecture for Information Exchange Through Shared Objects, CIB Workshop on Computer and Information In Construction, W78, August, pp 102-110

ISO (1994), Building Construction Core Model, Project Proposal, ISO Document, October.

Ito, K.(1993), Constraint Management for Concurrent Design and Construction Using and Object-Oriented Project Model, Proceeding of Fifth International Conference (V-ICCCBE), Computing in Civil and Building Engineering, Anaheim, California, USA, Vol. 2, pp.1588-1591.

Ito, K., Law, K.H., Levitt, R.E (1989), PMAPM: An Object Oriented Project Model for A/E/C Process with Multiple Views, CIFE Technical Report, No.10, Stanford University.

Jackson, M. A.(1983), System Development, Prentice Hall , London.

Jaselskis, E.J., Ashley, D.B. (1991), Optimal Allocation of Project Management Resources for Achieving Success, Journal of Construction Engineering and Management, ASCE, Vol. 117(2), pp. 321-340

Jayawardane, A.K.W., Price, A.D.F., Harris, F.C. (1995), Measurement of Brickwork and Blockwork Productivity: Part A, Building Research and Information, Vol. 23(2), pp. 81-86.

Jergeas, G. (1989), Detailed design and Constructability, a Ph.D. thesis, Civil Engineering Department, Loughborough University.

Jortberg, R.F. (1984), CII Constructability Committee's Status, Presented at the Constructability Productivity Conference, The University of Texas at Austin, Texas.

Karshenas, S., Haber, D. (1990), Economic Optimisation of Construction Project Scheluding, Construction Management and Economics, Vol.8(2), pp. 135-146.

Kartam, N. A. (1994), ISICAD: Interactive System for Integrating CAD and Computer-Based Construction Systems, Micro Computers in Civil Engineering, Vol. 9, pp. 41-51.

Kartam, N.A, Levitt, R.E., Wilkin, D.E. (1991), Extending Artificial Techniques for Hierarchical Planning, Journal of Computing in Civil Engineering, ASCE, Vol. 5(4), pp. 464-477.

Kartam, N.A., Levitt, R. E.(1990), Intelligent Planning of Construction Projects, Journal of Computing in Civil Engineering, ASCE, Vol. 4(2), pp. 155-176.

Kahkunen, K. (1993), Modelling Activity Dependencies for Building Construction Project Scheduling, Espoo, Technical Research Centre of Finland, VTT Publications, pp.153.

Kalay, Y.E. (1991), Computational Modalities of Evaluation and Prediction in Design, CADD Future 91, pp. 271-284.

Kalay, Y.E. (1991), Conclusion: Evaluating and Predicting Design Performance, Evaluating and Predicting Design Performance, Kalay, Y.E.(ed.), A Wiley-Interscience Publication, pp.399-404.

King, R. (1986), A database management system based on An Object Oriented Model, Expert Database Systems, Kerschberg, L. (ed.), pp. 443-467.

King, R. (1989), My Cat is Object-Oriented, Object Oriented Concepts, Databases, And Applications, Kim, W. and Lochovsky, F.H (ed.), ACM Press, New York, pp. 23-30.

Laufer, A.(1990), Essentials of Project Planning: Owner's Perspective, Journal of Management in Engineering, Vol.6(2), pp. 162-176.

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. Vol.5(3), pp. 243-266.

Laufer, A., Tucker, R.L. (1988), Competence and Timing Dilemma in Construction Planning, Construction Management and Economics, Vol. 6(4), pp. 339-355.

Leon, G. (1971), The Economics and Management of System Construction, Longman Group Limited.

Levitt, R.E., Kunz, J.C. (1985), Using Knowledge of Construction and Project Management for Automated Schedule Updating, Project Management Journal, Vol. 16(5), pp. 57-76.

Levitt, R.E., Kunz, J.C. (1987), Using Artificial Intelligence Techniques to Support Project Management, Journal of Artificial Intelligence in Engineering, Design, Analysis and Manufacturing, Vol. 1(1), pp.3-24.

Lewitt, R.E, Kartam, N.A., Kunz, J.C. (1988), Artificial Intelligence Techniques For Generating Construction Project Plans, Journal of

Construction Engineering and Management, ASCE, Vol. 114(3), pp. 329-343.

Lichtenberg, S.(1981), Real World Uncertainties in Project Budgets and Schedules. Proceedings of PMI INTERMET Joint Symposium, Boston MA, pp.179-193

Liu, L., Burns, S., Feng, C. (1995), Construction Time-Cost Trade-Off Optimization System, Proceeding of The Second Congress on Computing in Civil Engineering, Mohsen, J.P. (ed.), ASCE, pp. 1142-1149.

Luiten, G., Tolman, F. (1992), Computer Aided DfC (Design for Construction) In The Building And Construction Industries., CIB W78 Workshop On Computer Integrated Construction. Montreal. Canada, May. pp.318-329.

Luiten, G., Froese, T., Bjork, B. C., Cooper, G.. Junge, R ., Karstila, K.. Oxman, R. (1993), An Information Reference Model for Architecture. Engineering and Construction, Management of Information Technology for Construction, Mathur, K. *et al* (eds.), World Scientific Publishing Co.. Singapore, pp. 319-406.

Mansfield, C. (1983), Buildability : A Contractor's View, Architects' Journal. Vol. 117(7), pp. 46.

Mason, D.(1984), The CPM Techniques in Construction: A Critique. Transaction of The American Association of Cost Engineers(Montreal), pp. E.2.1.-E.2.10.

Martin, J. (1993), Principles of Object Oriented Analysis and Design., P.T.R. Prentice-Hall, Inc., New Jersey, USA.

McCahill, D. F., Bernold, L. E.(1989), Simulation for Constrution Planning and Control, Proceeding of Construction Congress, Excellence in the Constructed Project, ASCE, pp. 349-359.

McDermott, P. (1994), A Socio-Technical Analysis of the Building Process With Special Regard to Variations, Ph.D. Thesis, Department of Mechanical Engineering, Brunel University.

Miyatake, Y., Yamazaki, Y., Kangari, R.,(1993), The SMART System Project: A Strategy for Management of Information and Automation Technology in Computer Integrated Construction., Management of Information Technology for Construction, Mathur, K. *et al* (eds.), World Scientific Publishing Co., Singapore, pp. 407-420.

Miyatake, Y., Kangari, R.(1993), Experiencing Computer Integrated Construction, Journal of Construction Engineering and Management, Vol.119(2), pp. 307-322 .

Mohan, S.(1990), Expert Systems Applications in Construction Management and Engineering, Journal of Construction Engineering and Management, Vol. 116(1), pp.87-99.

Moore, D., (1996), Buildability Assessment and Development of An Automated Design Aid for Managing the Transfer of Construction Process Knowledge, Engineering, Construction and Architectural Management, Blackwell Science Ltd, pp. 29-46.

Morad, A. A., Beliveau, Y.J. (1989), CAD/CPM Data Interaction, Proceeding of ASCE, Computing in Civil Engineering-6th Conference, pp.588-596.

Morad, A.A., Beliveau, Y.J. (1991), Knowledge Based Planning System, Journal of Construction Engineering and Management, Vol. 117(1), pp. 1-12.

Munns, A.K., Li, Y.B., Lookman, A. A. (1994), Strategy for Computer Integrated Design Construction and Technology, Proceedings of ECPPM'94, Dresden/Germany, October 5-7, pp. 51-57.

Navinchandra, D., Sriram, D., Logcher, R. (1988), GHOST: Project Network Generator, Journal of Computing in Civil Engineering , Vol. 2(3), pp.239-254.

Ndekugri, I. E., McCaffer, R.(1988), Management Information Flow in Construction Companies, Construction Management and Economics, Vol. 6(2), pp. 273-294.

NCC (1990), SSADM Version 4 Reference Manual. Butterworth Press and National Computer Centre, Manchester.

NEDO (1975), The Public Client and the Construction Industries, HMSO.

Nevins, D.P., Zabilski, R.J. (1991). Graphical Database for Construction Planning and Cost Control, Preparing for Construction in the 21st Century, Proceeding of Construction Progress. ASCE, New York, pp. 266-271.

Nijssen, G.M., Halpin, T.A. (1989), Conceptual Schema and Relational Database Design: A Fact Oriented Approach, Prentice Hall.

O'Connor, J.T. (1985), Impacts of Constructability Improvement, Journal of Construction Engineering and Management, ASCE, Vol. 111(4), December, pp. 404-410.

O'Connor, J.T., Larimore, M. A., Tucker, R.L. (1986), Collecting Constructability Improvement Ideas, Journal of Construction Engineering and Management, ASCE, Vol. 112(4), December, pp. 463-475.

O'Connor, J.T., Rusch, S.E., Schulz, M.J.(1986), Constructability Concepts for Engineering and Procurement, A Report to The Construction Industry Institute(CII), University of Texas at Austin, Texas, May.

O'Connor, J.T., Rusch, S.E., Schulz, M.J.(1987), Constructability Concepts for Engineering and Procurement, Journal of Construction Engineering and Management, ASCE, Vol. 113(2), June, pp. 235-248.

O'Connor, J.T., Tucker, R. L.(1986), Industrial Project Constructability Improvement, Journal of Construction Engineering and Management, ASCE, Vol. 112(1), pp. 69-82.

Paulson, C.B.Jnr.(1976), Design to reduce Construction Costs, Journal of the Construction Division, ASCE, Vol.102(CO4), pp. 587-592.

Powell, M. (1983), Buildability : A Researcher's View, Architect's Journal, 177(10), March, pp.30.

Poyet, P. (1994), ATLAS Integration Tools, Proceedings of ECPPM'94, Dresden/Germany, October 5-7, pp.479-488.

Ramscar, M. (1994), Static Models and Dynamic Designs-An Empirical Impasse vs. An Inductive Solution. Proceedings of ECPPM'94, Dresden/Germany, October 5-7, pp. 69-76.

Rauch-Hindin, W.B. (1988), A Guide to Commercial Artificial Intelligence, Prentice Hall, New Jersey.

Report from the Steering group of the Technology Foresight Programme, May (1995), Progress Through Partnership Part 2, Construction, HMSO Publication.

RIBA (1980), A Plan of Work For Design Team Operation, RIBA Publication.

Riley, M.J., Sabet, H.(1993), The Integrated Information System for AEC Projects, Civil-Comp 93, The Fifth International Conference on Civil & Structural Engineering Computing and AI, Edinburgh,

Rolston, D.W.(1988), Principles of Artificial Intelligence and Expert Systems Development, McGraw Hill, New York.

Rolland, C., Cauvet, C.(1992), Trends and Perspectives in Conceptual Modelling, Conceptual Modeling DataBases, and Case (An Integrated View of Information System Development), Loucopoulos, P & Zicari, R.(ed.), John Wiley & Sons, Inc, pp. 27-48.

Rosenman, M. A.(1993), Dynamic Decomposition Strategies in the Conceptual Modelling of Design Objects, Concurrent Engineering :Research and Applications, Vol. 1(1), March.

Ross, D.T., Schoman, K.E. (1977), Structured Analysis for Requirement Definition, IEEE Transactions on Software Engineering, SE-3(1), pp. 1-65.

Rumbaugh, J., Blaha, M., Premerlani, W., Eddy, F., Lorensen, W. (1991), Object- Oriented Modelling and Design, Prentice Hall International.

Sanvido, V.E. (1990), An Integrated Building Process Model, Technical Report No.1, Computer Integrated Construction Research Program, Department of Architectural Engineering, the Pennsylvania State University, PA 16802.

Sanvido, V. E., Medeiros, D.J. (1990), Applying Computer-Integrated Manufacturing Concepts to Construction., Journal of Construction Engineering and Management, Vol. 116(2), June, pp. 365-379.

Sanvido, V. E. (1992), Penn State Computer Integrated Construction Research Program., CIB W78 workshop on Computer Integrated Construction, Montreal, Canada, May, pp. 394-400.

Sanvido, V. E., Anzola, G., Bennett, S., Cummings, D., Hanlon, E., Kuntz, K., Lynch, T., Messner, J., Potter, K., Riley, D., Yoshigi, T., (1992), Information Architectural for Computer Integrated Construction (Draft Report), Computer Integrated Construction Research Program, Department of Architectural Engineering, the Pennsylvania State University, PA 16802.

Sause, R., Martini, K., Powell, G.H., (1992), Object Oriented Approaches for Integrated Engineering Design Systems. Journal of Computing in Civil Engineering, ASCE, Vol. 6(3), pp. 248-265.

Scherer, R.J.(1994), EU-Project COMBI- Objectives and Overview, Proceedings of ECPPM'94, Dresden/Germany, October 5-7, pp. 503-510.

Schmitt, G., (1991), Design for Performance, Evaluating and Predicting Design Performance, Kalay, Y.E. (ed.), A Wiley-Interscience Publication, pp.83-100.

Seeley, I.H. (1984), Quantity Surveying Practice, MacMillan Publishers Ltd.

Shaked, O., Warszawski, A. (1995), Knowledge - Based System For Construction Planning of High - Rise Buildings, Journal Of Construction Engineering and Management, Vol.112(2), pp.172-182.

Shtub, A. (1988), The Integration of CPM and Material Management in Project Management, Construction Management and Economics, Vol.6(4), pp.261-272.

Simon, K. L., Thornberry, H. L., Wickard, D. A.(1988), Simulation System for Construction Planning and Scheduling, Presented at the Joint ASME/IEEE Power Generation Conference, American Society of Mechanical Engineers, Philadelphis, Pa.

SMM7 (1987), Standard Methods of Measurement Of Building Works, Seventh Editions, RICS & BEC, December.

Smith, S. (1992), Towards An Intelligent Planning System. International Journal of Project Management, Vol. 10(4), pp.213-218.

Stone, P.A. (1983), Building Economy : Design, Production and Organisation A Synoptic View, 3rd Edition, Pergamon Press.

Steiner, G.A. (1979), Strategic Planning, What Every Manager Must Know, The Free Press, Collier Macmillan Publishers London.

Stove, R.N. (1984), Analysis of CAD/CAM Applications, Prentice-Hall, Inc., N.J.

Stretton, A., Steven, G. (1989), An Expert System for Estimating Indicative Construction Times for Multi-storey Buildings at Concept Stages, Australian Conference on Expert Systems in Engineering, Architecture and Construction, Gero, J.S. & Sudweeks, F.(ed.), Sydney, pp. 29-43.

Tah, J.H.M., Howes, R., Iosifidis, P.(1994), Capturing Semantic data in CAD for Construction Project Planning, Proceedings of ECPPM'94, Dresden/Germany, October 5-7, pp. 287-293.

Tate, A. (1985), A Review of Knowledge-Based Planning Techniques. The Knowledge Engineering Review Journal, Vol. 1(2), pp. 89-111.

Tatum, C.B. (1987), Improving Constructability During Conceptual Planning, Journal of Construction Engineering and Management, Vol. 133(2), pp.191-207.

The Building Centre Trust (1991), Building IT 2000, A Study by Expert on the Future of Building and Information Presented on a Hypertext Database May 1991.

Thorpe, A., Baldwin, A.N., Lewis, T. (1994), Data Exchange Standards for The Construction Industry, The International Journal of Construction Information Technology, Vol.2(2), pp.65-84.

Tom, P. (1995) How Can a Model Represent a Building for a Computer Specification Processor?, Computing in Civil and Building Engineering, Pahl & Werner(ed.), Balkema, Rotterdam,pp.323- 329.

Turk, Z. (1992), Object Oriented Modeling Techniques and Integrated CAD, CIB W78 & CBS, Montreal, May, pp. 471-482.

Turk, Z. (1994), Document Centered Approach to Design Process Modeling, Proceedings of ECPPM, Dresden/Germany, pp. 265-272.

Turk, Z., Isakovic, T., Fischinger, M. (1994), Object Oriented Modeling of Design System for RC Building., Journal of Computing in Civil Engineering, Vol. 8(4), October, pp.436-453.

Underwood. J. (1995), Integrating Design and Construction to improve constructability through an effective usage of IT., Ph.D. thesis, Department of Surveying, Salford University.

Underwood, J ., Alshawi, M.(1996), Project Estimates & Monthly Interim Valuation Certificates Generation in an Integrated Construction Environment, EPSRC and Taylor Woodrow Funded Research, University of Salford.

Van Leeuwen, J. P., Wagter, H., Oxman, R. M. (1995), A Feature Based Approach to Modelling Architectural Information, CIB Workshop on Computers and Information in Construction, August, pp.260-269.

Van Nederveen, S. (1993), View Integration in Building Design, Management of Information Technology for Construction, Mathur, K. *et al* (eds.), World Scientific Publishing Co., Singapore, pp 209-221.

Vincent, SPR. (1993), Integrating Different Views of Integration., Integration of Construction Information, Science and Engineering Research Committee N & N Workshop.

Watson, A. (1993), To Product Models and Beyond, Integration of Construction Information, Science and Engineering Research Committee N & N Workshop.

Watson, A., Crowley, A. (1994), CIMSTEEL Integration Standards, Proceedings of ECPPM, Dresden/Germany, pp. 491-493.

Walker, A. (1989), Project Management in Construction, 2nd.Edition, Granada, England.

William, B. (1983), Buildability : A Quantity Surveyor's Veiw, Architects' Journal, Vol.177(7), pp. 46.

Wix, J. (1989), Common Standard for Data Exchange, Construction Computing, Spring, pp. 13-15.

Yamazaki, Y.(1991) , Integrated Design and Construction Planning by Knowledge based Systems, Preparing for Construction in the 21st Century; Construction Congress 91, ASCE, New York, pp. 400-405.

Yamazaki, Y. (1993), ICPS: Integrated Construction Planning System by Object Oriented Planning Models., Proceeding of Fifth International Conference (V-ICCCBE), Computing in Civil and Building Engineering, Anaheim, California, USA, pp. 295-302.

Yamazaki, Y. (1994), An Object -Oriented Process Modeling to Support Cooperative Planning in Industrialized Building Construction Project, Computing in Civil Engineering, pp. 998-1005.

Yamazaki, Y. (1995), An Integrated Construction Planning System Using Object-Oriented Product and Process Modeling, Construction Management and Economic, Vol. 13(5), pp. 427-434.

Yau, N. (1992), An Object Oriented Project Model for Integrating Building Design, Construction Scheduling and Cost Estimating For Mid Rise Construction., PhD Thesis, Department of Civil Engineering, University of Illinois, Urbana-Champaign.

Yau, N.J., Melin, J.W., Garrett, J.H., Kim, S.(1991), An Environment for Integrating Building Design, Construction Scheduling and Cost Estimating, Proceeding of Seventh ASCE Conference on Computing in Civil Engineering, Washington D.C., pp. 222-232.

Yourdon, E., Coad, P. (1991), Object-Oriented Analysis. Yourdon Press Computing Series, New Jersey, USA

Yu, C., Krizan, S., Ishii, K. (1993), Journal of Intelligent Manufacturing, No.4, pp.199-208

Zozaya-Gorostiza, C., Hendrickson, C., Rehak, D. (1989). A Knowledge-Based Process Planning for Construction and Manufacturing, Academic Press, Inc., San Diego, California.

Appendix A

Basic Operation Time for formwork

The following Basic Operation Times are obtained by combining the Basic Element Times and Ancillary Allowances

B.T. for
External Beams = ((25.15 x 1.35) + (3.75 + 2.56)1.24) x 2 x B x W
= 83.5 B.W

B.T. for
Internal Beams = (3.75 + 2.56 + 2.56) 1.24 x L
= 11.0 L

B.T. for Deck = 10.05 x 1.24 x A
= 12.5 A

B.T. for boxing
internal = 10 x 1.24 x A
= 12.4 A

Basic Operation
Times (mins) = 83.5 B.W + 11.0 L + 12.5 A + 12.4 A

where: B = Slab breadth (m)
W = Slab width (m)
A = Slab area (m2)
L = Length of internal beams (m)
N = Internal columns

Basic Operation
Times (mins)
for Column = 7.27 + 8.31L + 8.68 WL + 7.44 W
using traditional
timber form.

Basic Operation
Time (mins)
for erecting Column (hrs) = 24.4 x (30.05 + 9.82 h + 10.47(b + d) 2h) / 60
using metal
shutter

Basic Operation
Time (mins)
striping Column (hrs) = (11.51 x h) / 60
using metal
shutter

where h = height (m)
b = breadth (m)
d = depth (m)

Basic Operation
Time (mins)
steel panel shutter = (80.6 + 21.77 x L x D) 1.284
for ground beam

where L = Length of beam
D = Depth of beam

Basic Operation Time for concreting work

For column which require vibrating, trowelling once and covering, the Basic Operation Times (B.O.T) can be obtained by applying one of the following equations.

Direct pour B.O.T (mins) = (55.7 + 35.62V + 3.57A) x 1.0775
Using Skip B.O.T (mins) = (55.7 + 35.62V + 3.57A) x 1.130
Using Pump B.O.T (mins) = (65.1 + 36.17V + 3.57A) x 1.0775

For slab which require vibrating, trowelling once and covering, the Basic Operation Times (B.O.T) can be obtained by applying one of the following equations.

Direct pour B.O.T (mins) = (51.4 + 6.81V + 4.57A) x 1.0775
Using Skip B.O.T (mins) = (51.4 + 6.81V + 4.57A) x 1.130
Using Pump B.O.T (mins) = (60.7 + 7.36V + 4.57A) x 1.0775

For beam which require vibrating, trowelling once and covering, the Basic Operation Times (B.O.T) can be obtained by applying one of the following equations.

Direct pour B.O.T (mins) = (67.0 + 10.04V + 3.57A) x 1.0775
Using Skip B.O.T (mins) = (67.0 + 10.04V + 3.57A) x 1.130
Using Pump B.O.T (mins) = (76.4 + 10.59V + 3.57A) x 1.0775

where V = volume m3
A = Area

Basic Operation Time for brick wall

Measurement of brickwork and blockwork productivity: Part A
A.K.W. Jayawardane, A.D.F Price and F.C.Harris
Building Research and Information, Vol.23, No.2 1995.

For 225 mm brick-thick wall

A) $BT = 361.4N + 89.4NK + 9.73A + 0.61N_1*N_2 + 0.43N_2$
pointed with mortar supplied by a small mixer operated by labourer

B) $BT = 361.4N + 89.4NK + 1.88A + 0.61N_1*N_2 + 0.43N_2$
for rough work with labourer operated mixer

C) $BT = 344.4N + 89.4NK + 1.88A + 0.61N_1*N_2 + 0.43N_2$
for rough work with ready mixed mortar

D) $BT = 344.4N + 89.4NK + 9.73A + 0.61N_1*N_2 + 0.43N_2$
for rough work with ready mixed mortar

E) $BT = 3.61.4N + 89.NK + 9.73A + 0.41N_1*N_2 + 0.43N_2$
pointed work with labourer operated mixer

F) $BT = 0.19*t + 0.047A*t*K + 9.73A + 8.134N_1*N_2*h + 5.73N_1*h$
for different type of wall thickness.

where

A = surface area of one side band on centre line dimension (m2)
N = number of bricks (thousands)
N_1 = number of 'L' corners in the construction (two dead ends can be considered as one corner)
N_2 = total number of courses in all sides (total number line setting)
K = factor introduced to cater for different amount of ancillary work depending on type of construction(1= House)
t = thickness of wall (mm)
h = height of wall (m)

Basic Operation Time for insitu fixing of slab reinforcement

	Average bar diameter (mm)		
	10	12	16
Position bottom layer	236	164	67
Tie bottom layer	595	413	167
Block out	128	89	36
BOTTOM LAYER TOTAL	959	666	270
Position chairs	137	95	39
Position top layer	36	25	10
Tie top layer	773	536	217
TOP LAYER TOTAL	946	656	266
Edge Steel	3250	2256	915

Additional Work
Column starters = 10.0 minutes per column
Ancillary work = 10% (T.B.T + A.W)
Operation Transportation = 65 mins/tonne

B.O.T = ([B.E.T + A.W] x A.A + O.T + S.T) x N .P.W

where
B.E.T = Basic Element Time
A.W = Additional Work
A.A = Ancillary Allowances

O.T = Operation Transportation
S.T = Site Transportation

B.O.T = ([666 + 656] x 1.093 + 6.5 + 40) x 1.22
= 1820 mins/tonne
= 30.3 hours/tonne

Basic Operation Time for insitu fixing of beam reinforcement

	Weight per metre (kg/m)		
	10	40	70
Position steel	80	140	220
Tie steel	180	228	276
Position steel	15	10	5
Total	275	378	501

Ancillary Allowance	40% (T.B.E.T)
Operation Transporation	75

B.O.T = ([B.E.T + A.W] x A.A + O.T + S.T) x N .P.W

where
B.E.T = Basic Element Time
A.W = Additional Work
A.A = Ancillary Allowances
O.T = Operation Transportation
S.T = Site Transportation
N.P.W = Non Productive Work

B.O.T = ([378 + 0] x 1.40 + 75 + 40) x N.P.W
= 835 mins/tonne
= 13.9 hours/tonne

Basic Operation Time for prefabricated fixing of beam reinforcement

	Reinforcement weight per metre (kg/m)		
	10	40	70
Position steel	43	90	138
Tie steel	102	146	190
Position block	15	10	5
Position cage	40	45	50
Tie link steel	48	44	40
Total	248	335	423
Ancillary Allowance	40% T.B.E.T		
Operation Transportation		51	

B.O.T = ([B.E.T + A.W] x A.A + O.T + S.T) x N .P.W

where
B.E.T = Basic Element Time
A.W = Additional Work
A.A = Ancillary Allowances
O.T = Operation Transportation
S.T = Site Transportation
N.P.W = Non Productive Work

B.O.T = ([335 + 0] x 1.40 + 51 + 40) x 1.22
= 685 mins/tonne
= 11.4 hours/tonne

Basic Operation Time for in site fixing of column reinforcement

	Diameter of main bars (mm)				
	32	25	20	16	12
Tie steel (per ties)	0.64	0.6	0.54	0.48	0.43
Position bars (per metre)	2.54	2.09	1.39	0.7	0.3
Total	3.18	2.69	1.93	1.18	0.73
Ancillary allowance	20% (T.B. E.T)				

B.O.T = ([B.E.T + A.W] x A.A + O.T + S.T) x N .P.W

where

B.E.T = Basic Element Time
A.W = Additional Work
A.A = Ancillary Allowances
O.T = Operation Transportation
S.T = Site Transportation : assuming S.T = 40
N.P.W = Non Productive Work

B.O.T = ([0.54 x 44 + 1.39 x 12] x 1.20 + S.T) x 1.22
= 48.6 x 1.22 mins/column + 40 x 1.22 mins/tonne
= 1.0 hour/column + 0.8 hour/tonne

Basic Operation Time for in site fixing of prefabricated column reinforcement

	Weight per metre (kg/m)		
	5	10	20
Position steel	40	40	51
Tie steel	102	102	147
Position blocks	15	15	15
Position Cage	80	80	80
Tie to starters	320	320	320
Total	557	557	613
Ancillary allowance	20% (T.B.E.T)		
Operation Transportation	51		

B.O.T = ([B.E.T + A.W] x A.A + O.T + S.T) x N .P.W

where
B.E.T = Basic Element Time
A.W = Additional Work
A.A = Ancillary Allowances
O.T = Operation Transportation : assuming O.T = 51
S.T = Site Transportation : assuming S.T = 40
N.P.W = Non Productive Work

B.O.T = ([557 + 0] x 1.20 + 51 + 40) x 1.22
= 925 mins/tonne
= 15.4 hours/tonne

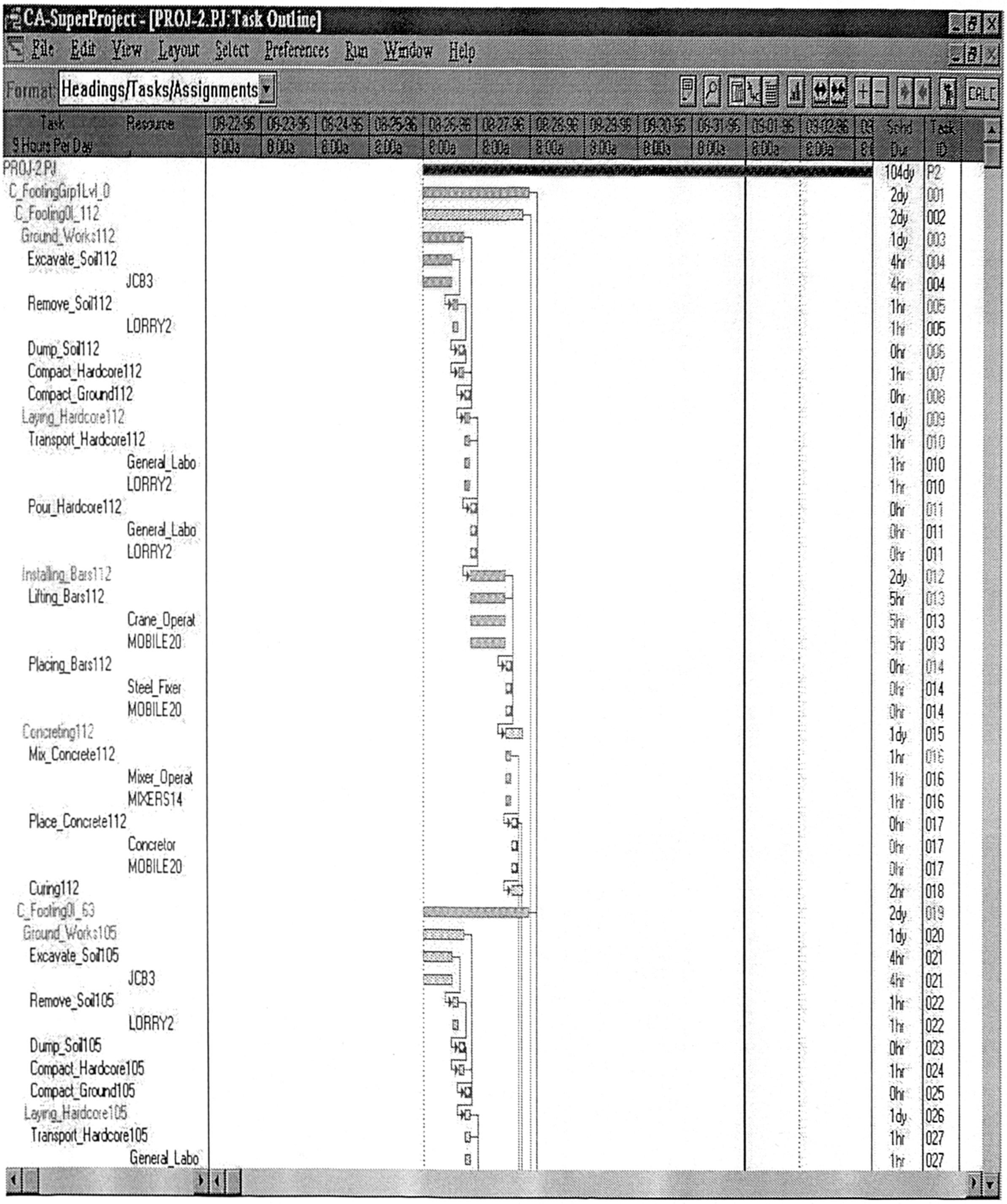
Cement Mortar to External and Internal work to walls (Geddes, S, 1985).

Description	Unit	Thickness in mm	Plasterer hrs	Labourer hrs
Render on walls 1st coat & score for 2nd coat	m2	12	0.24	0.24
Render on walls 1st coat & score for 2nd coat	m2	19	0.36	0.36
Render on walls & float for finishing coat	m2	12	0.3	0.3
Render on walls & float for finishing coat	m2	19	0.42	0.42
2nd Coat, screeded and floated for finishing coat	m2	6	0.36	0.36
Finishing coat trowelled or stucco	m2	6	0.42	0.42
Render and wet rough cast	m2	19	0.96	0.96
Render and pebble dash	m2	19	1.08	1.08

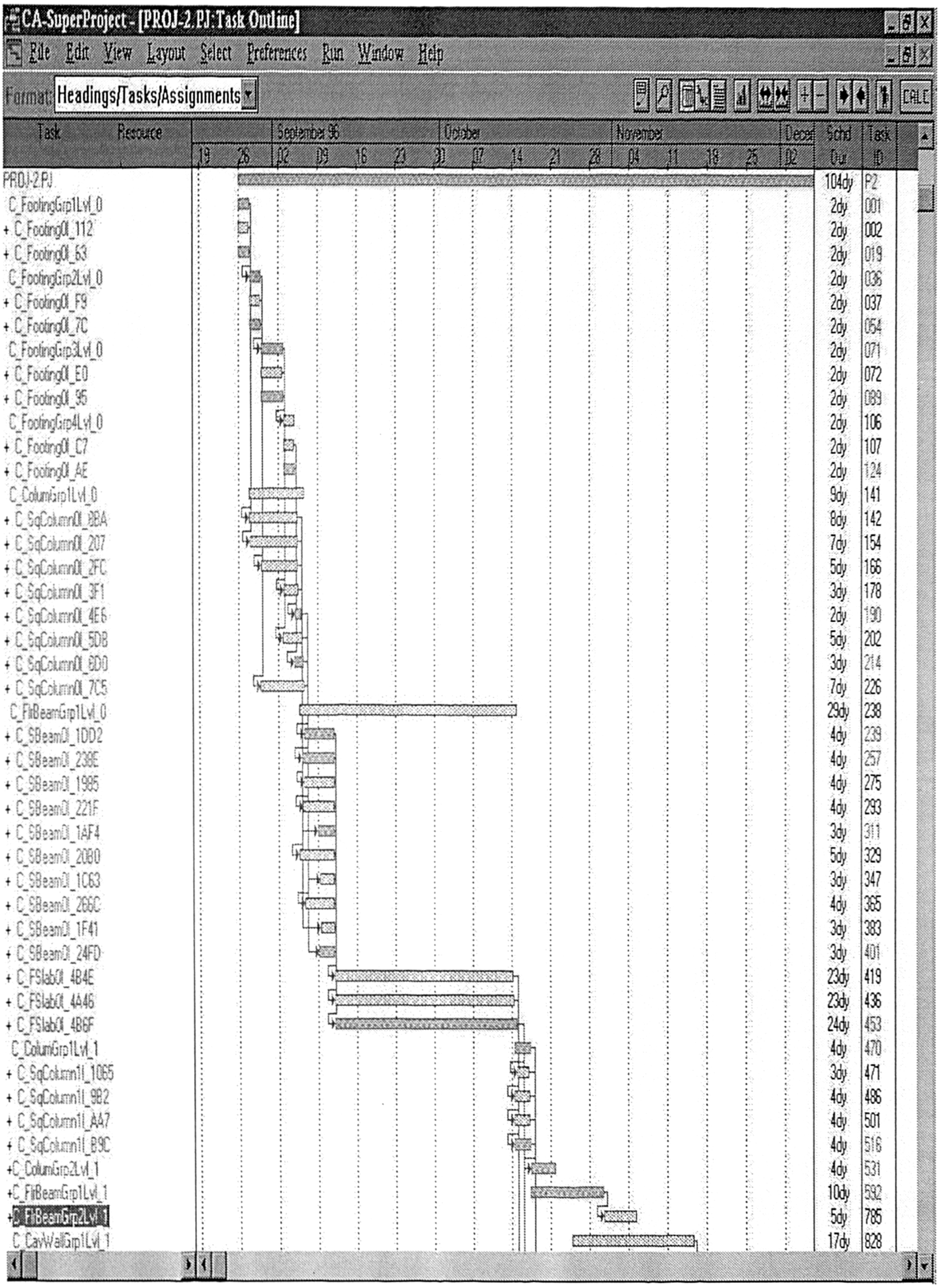
Cement mortar external and internal work to floors (Geddes, S, 1985).

Description	Unit	Thickness in mm	Plasterer hrs	Labourer hrs
Render in one coat, screed & trowel	m2	15	0.37	0.37
Render in one coat, screed & trowel	m2	22	0.41	0.41

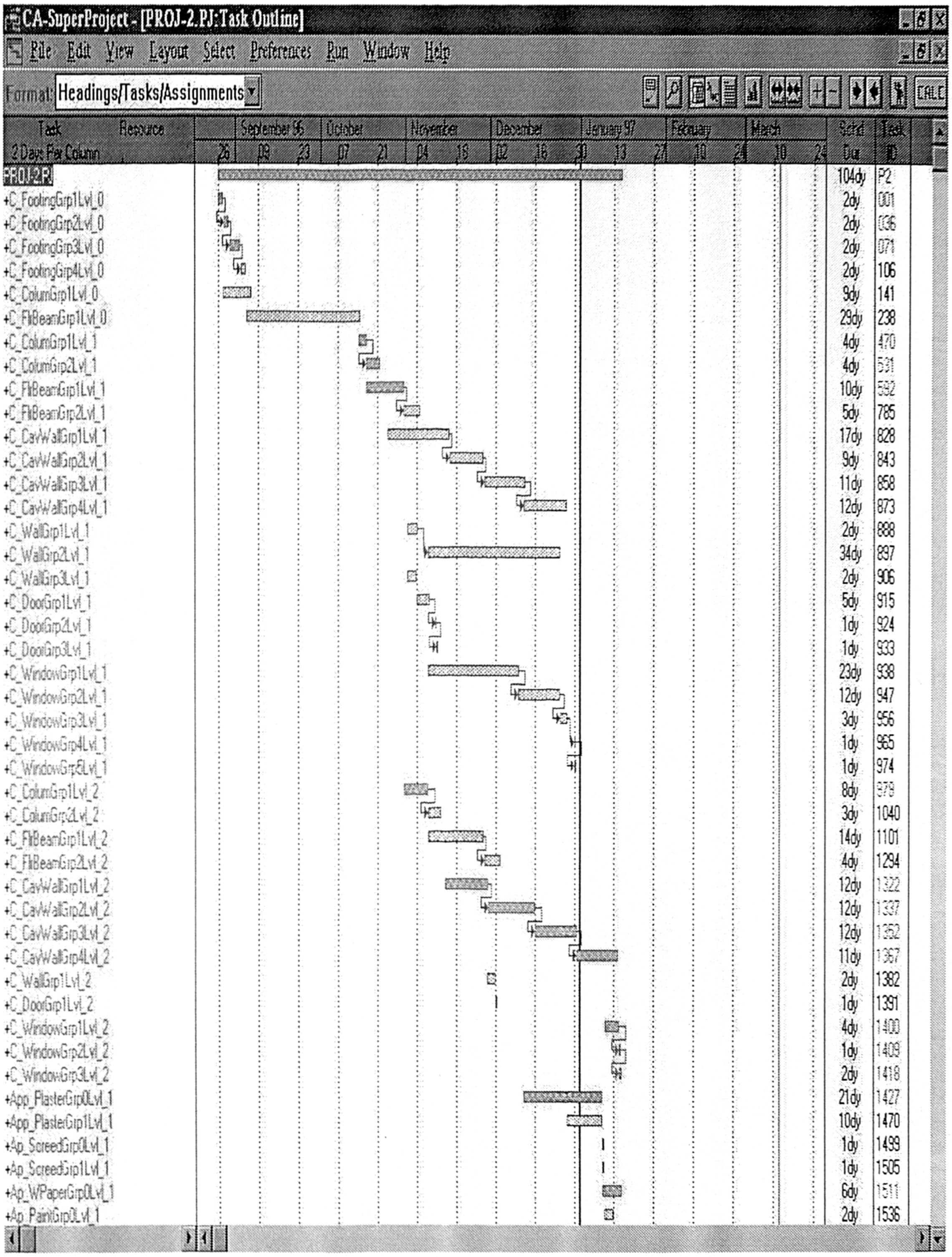
Appendix B



Example of the Detail Plan

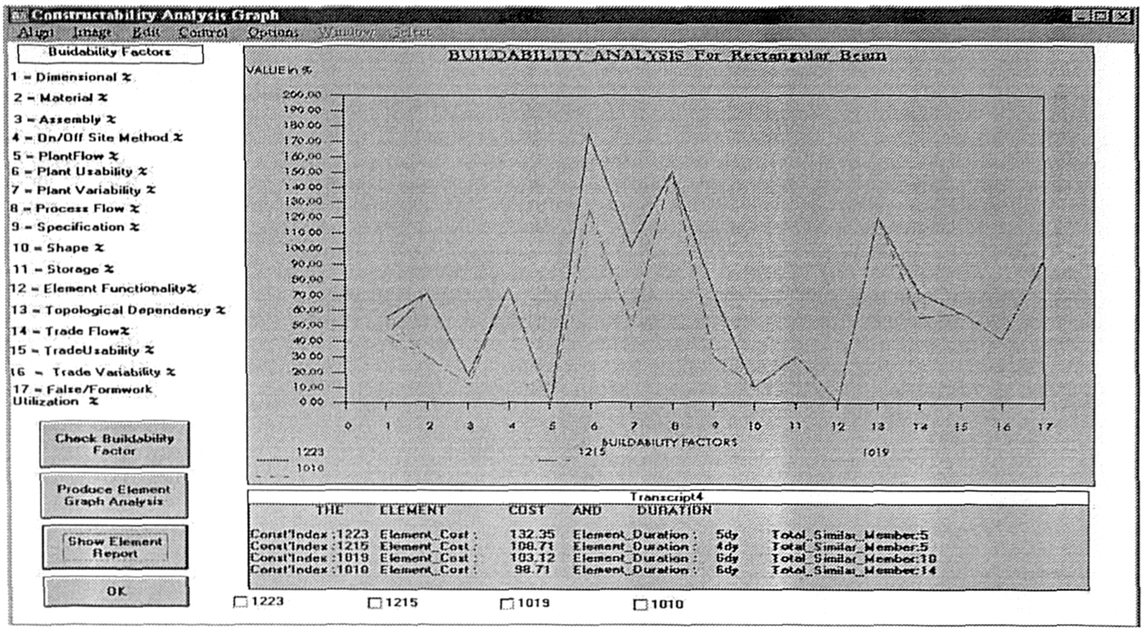


Example of the Executive Plan

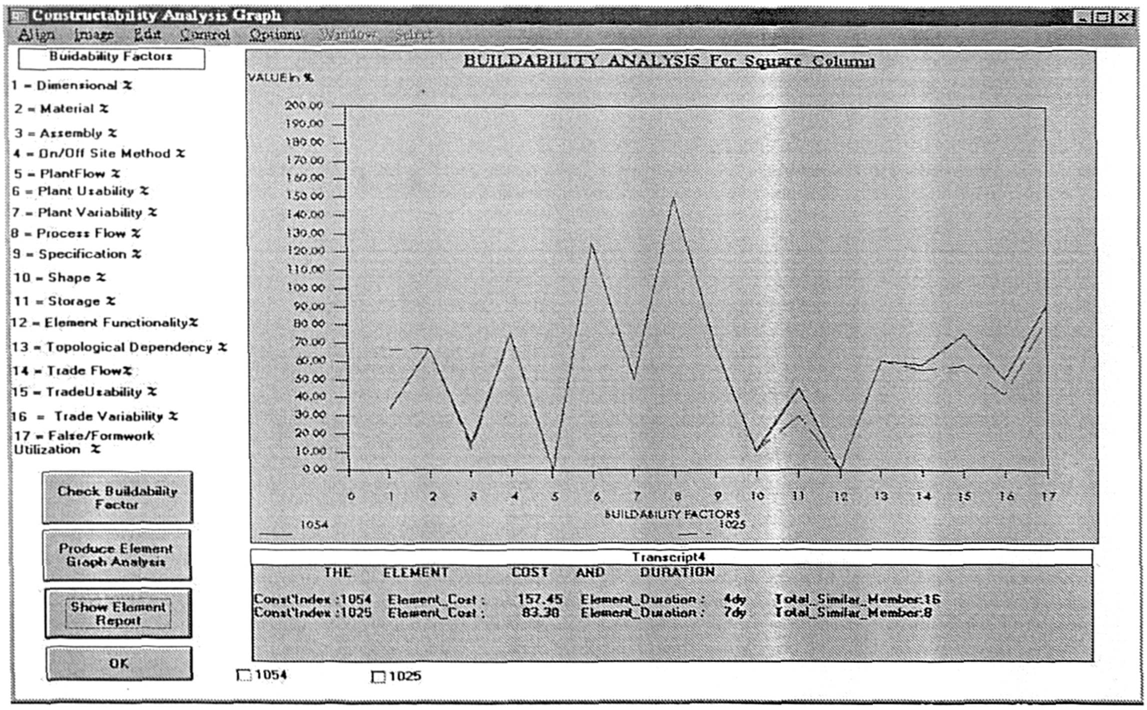


Example of the Master Plan

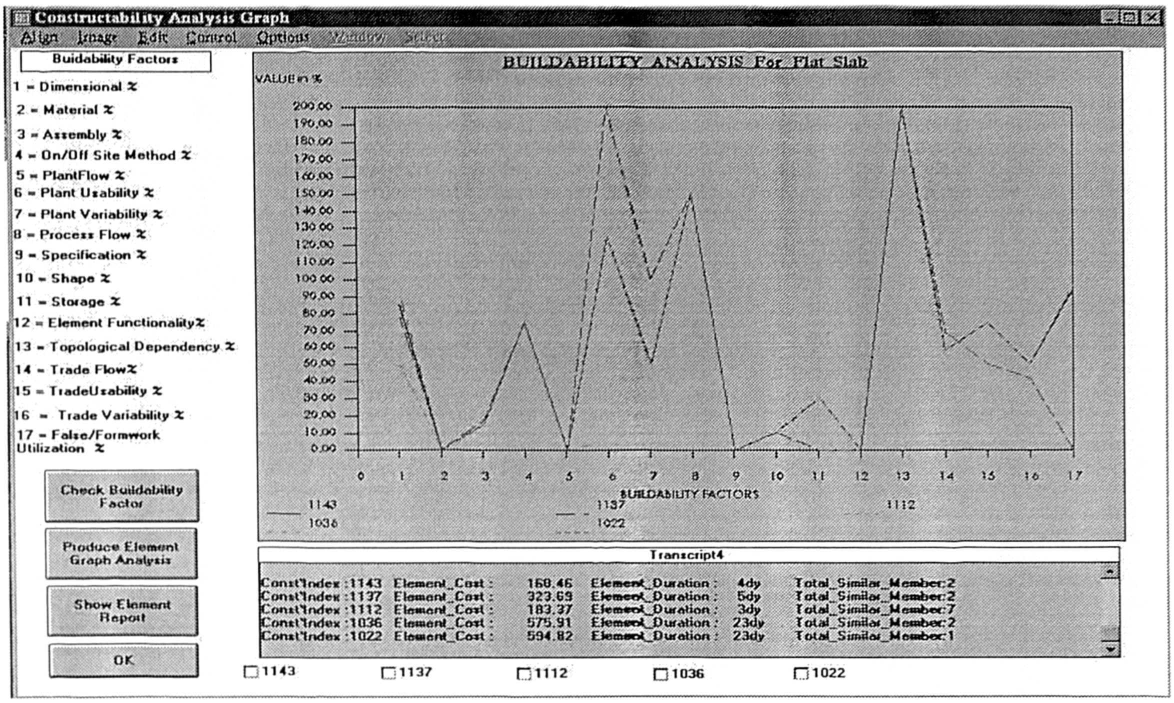
Appendix C



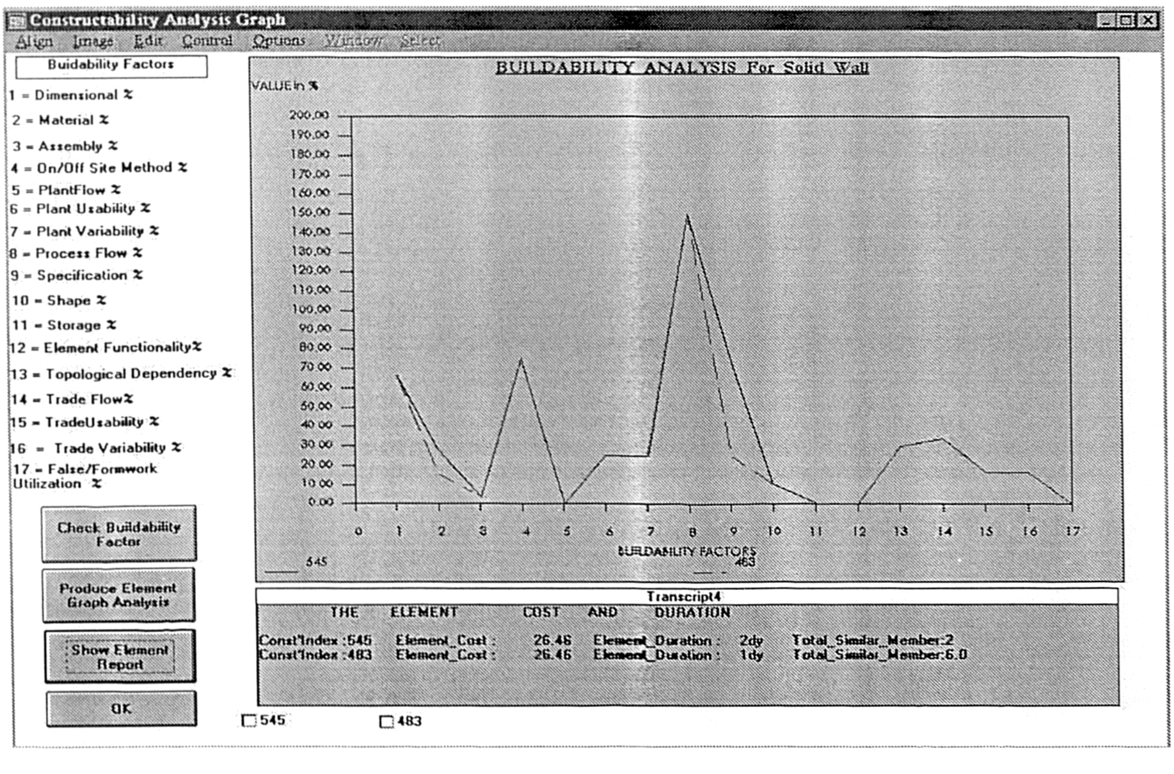
Buildability evaluation result for rectangular beam.



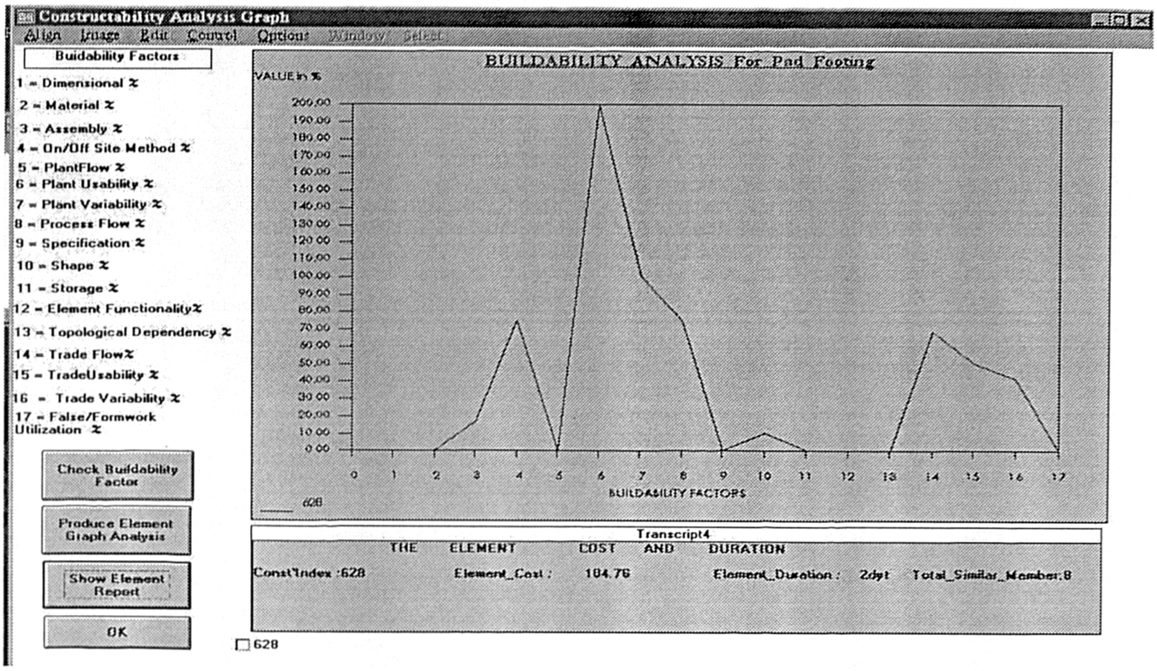
Buildability evaluation result for square column.



Buildability evaluation result for slab.



Buildability evaluation result for solid wall.



Buildability evaluation result for footing.