COMPUTER VISULISATION SUPPORT FOR BUILDABILITY

by

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For my Mother

and

in memory of my Father

LIST OF CONTENTS

ABSTRACT

The construction industry has a reputation for low productivity, waste, low use of new technologies, and poor quality (Egan, 1998; Wakefield & Damrienant, 1999). It is estimated that up to 30% of construction is rework, and recognised that site teams spend too much time and effort making designs work in practice (Egan, 1998). The aim of the research project was to develop a visualisation and communication environment that would assist design teams in communicating design details that may be problematic for construction teams. The investigation was based on the need for a tool that facilitates detail design information communication. The VISCON (computer visualisation support for buildability) environment provides support for general information sharing in the context of a collaborative building project. This prototype is Web based and can be accessed from any location. This will allow for construction information to be readily communicated and shared between head offices and construction sites and any other locations to provide better visualisation of design details. Three scenarios were developed as case studies for demonstration purposes based on real projects. These case studies used a paper factory, a bay barrage building and a swimming pool recently constructed at Loughborough University. In the development of the case studies, 3D models were produced using components from the selected prototype buildings that may inherently be difficult to assemble. The VISCON prototype demonstrates the various functionalities of the system in creating intricate design details that can be animated or interacted with in real time.

The main achievements of the research are:

- The review of buildability problems and their causes during the construction stage of a facility;
- The development of an architecture for a computer visualisation tool for buildability (VISCON);

- Implementation and validation of the proposed system (VISCON) through the use of a number of case studies. The system was found to be useful and demonstrated that computer visualisation tools provide considerable potential in improving clarity of information and also a new way of visualising and solving design problems that arise during the construction stage of a project. It also demonstrated the ease of use of the proposed system, and its efficiency and application to the construction industry.

The research concludes that the use of computer visualisation can improve the construction project delivery process by providing guidance on how components are assembled together and how buildability problems can be solved during the construction stage. Furthermore, the use of effective communication tools will improve collaboration between construction and design practitioners.

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LIST OF CHAPTERS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

AEC	Architecture, Engineering and Construction
CAD	Computer Aided Design
HTML	Hyper Text Markup Language
ISO	International Standards Organisation
IT	Information Technology
MB	Megabytes
MHz	Megahertz
PC	Personal Computer
RAM	Random Access Memory
RIBA	Royal Institute of British Architects
VR	Virtual Reality
VRML	Virtual Reality Modelling Language

Chapter One
General Introduction

CHAPTER ONE

1 INTRODUCTION

1.1 INTRODUCTION

This chapter introduces the research work presented in this thesis. It describes the background, aim, objectives and methodology of the research, and provides a guide to the content of the thesis.

1.2 BACKGROUND

The construction industry is regarded as the largest economic sector in the world. It typically represents 10-25% of the gross national product (GNP) of a nation (Veeramani et al. 1998). In the UK, output from the construction industry was about £58 billion in 1998, which is equivalent to around 10% of the GNP (Egan, 1998). In the US, output from the construction industry is around $850 billion per year (equivalent to 13% of GNP) and employs 10 million people (Kalay, 1998). The construction industry has a reputation for low productivity, waste, low technology, and poor quality (Egan, 1998; Wakefield & Damrienant, 1999). It is estimated that up to 30% of construction is rework, and recognised that site teams spend too much time and effort making designs work in practice (Egan, 1998).

A recent study by the Construction Industry Institute has found that there is a strong correlation between communication and project success (CII, 1997). The study indicates that if a project team communicates effectively, there is a high probability for project success in terms of time, quality and cost. Today, projects are increasingly complex in terms of design, construction methods, and materials used. At the same time, clients demand better quality and faster schedules to meet the demands of global competition. In order to meet these challenges clients, contractors and designers must communicate ideas and design information quickly, accurately, effectively and on time. Recent studies show that when firms adopt IT, they can improve information flow and optimise the way the team communicates (Basu, 1996; Back & Bell 1994; Hammer & Champy, 1993).

Communication in construction has been identified as a problem area (Latham, 1994; Egan, 1998 and Gorse et al, 1999). Many communication problems develop during the construction stage between designers and contractors. Design information such as drawings, specifications and construction method statements need to be exchanged between team members. The design of a building is rarely complete before the construction phase starts. As a result, design details are developed while the construction process is underway. The time needed to check the design details can therefore be tight as time spent identifying missing information or interpreting unclear design details, may cause delays or result in constructing building parts incorrectly. One of the main difficulties during the construction stage is to ensure that adequate information from other parties is received in time to enable construction teams to construct complicated interfaces. If this information is delayed, assumptions may have to be made. If assumptions are incorrect, rework may have to take place (Tommelein & Chua, 1998), which causes an increase in costs and delays to the construction process. Therefore, effective communication tools are needed to ensure information is processed correctly and on time to enable the construction process to run smoothly.

Information available to architects at an early stage of a project may be limited. However, the design process depends on the flow of information that does not include the contractor in the early stages of a project. This excludes skills and expertise that the contractor can bring to the design stage. These skills and knowledge include, resources utilisation, and buildability. The exchange of information concerns all participants in the construction process, including those involved in communicating technical details of the design to site teams (Griffith, 1989). Buildability information is an important part of the design and construction of a project (Ferguson, 1989) as designers are sometimes removed from the construction process. This lack of knowledge and absence of adequate information often results in high costs and in some cases, faulty construction (Russell et al, 1994).

During the construction process, builders face a number of problems. One of these problems is interpreting design details, which can be complicated and difficult to understand and build. They sometimes spend too much time and effort trying to understand the design intent and may need help from the site management team (Bennett, 1985). The site management team may in turn need to contact the designer to clarify these details and how they can be implemented. This may require additional drawings to be produced. It is estimated that nearly 45% of all quality problems occurring on construction sites are due to inadequate project information (Snook, 1995).

Computer visualisation has become the field that designers are currently seeking to exploit as a new technology to cope with a rapidly changing construction industry. (Newton, 1998). Project information visualisation is not only important at the design stage but it is also becoming increasingly important at construction stage. It can be a valuable tool for enhancing existing systems with respect to construction sequence, equipment access, completed work and assembling difficulty areas (Alshawi and Underwood, 1999). In addition to that, visualisation with good communication could create the necessary links between site and design teams to collaborate to solve buildability problems that may arise during construction (Construct IT, 1995).

In view of the above, there is the need for a visualisation system that is capable of providing an effective tool for communicating buildability graphical information between design and construction teams. It is this need that this research project seeks to address.

1.3 HYPOTHESIS AND THE RESEARCH QUESTIONS

The hypothesis of the research; is that traditional methods and tools of presenting design details and intents, and communication media between designers and construction teams are not adequate enough. Therefore the use of computer visualisation tools will improve communication between design offices and site teams and ensure proper and correct implementation of design intents. It also creates the necessary links between site and design teams to collaborate solving buildability problems that may arise during construction stage.

The research questions addressed are:

- Are traditional information tools adequate to communicate design information to construction teams?
- What are the uses of and attitudes towards, computer visualisation and communication tools within the construction industry?
- What are the buildability problems and their causes?
- How would computer visualisation and communication tools help in dealing with buildability problems?

These research questions explore different aspects of the research problem. Chapter 3 discusses how these research questions were identified through a review of previous research efforts.

1.4 THE AIM AND OBJECTIVES OF THE RESEARCH

The main aim of this research is to study the potential use of computer visualisation and computer mediated communication in building construction to:

- Eliminate waste and rework in construction caused by improper communication, misunderstanding of design details and conflicting design information;

- Communicate project information properly, correctly and on time, and;

- Create a rich computer-generated environment in which users can communicate, exchange design information and collaborate with each other. This will enable people to join in team meetings and discussions, irrespective of their location, to solve design problems that may arise during construction.

To achieve this aim the specific objectives of the research project are to:

1. Review existing visualisation tools and communication infrastructures in design and construction companies.

2. Review the type of information used and difficulties experienced especially at site level.

3. Develop a system specification for communicating buildability information between design and construction teams.

4. Develop a framework for information flow between design and construction teams during the construction stage of a project.

5. Develop a prototype system using computer visualisation to support communication of buildability information.

6. Evaluate, using appropriate examples, the effectiveness of the prototype system.

1.5 METHODOLOGY

This system should be capable of being implemented in real life; therefore several research methods have been used. Triangulated research studies approaches were adopted, these employ two research techniques: qualitative and quantitative. The adoption of the triangulated approach was to reduce or eliminate the disadvantages of each individual approach while benefiting from both methods (Fellow & Liu, 1997).

In pursuit of the aim and objectives as stipulated earlier in Section 1.3, the research scheme in Figure 1-1 comprising six stages was adopted. The following actions were taken:

1. Literature review of previous studies was undertaken for several purposes: help delimiting the problem; explore new approaches to solving the problem; avoid errors in planning the research study; and find new sources of data. This survey revealed that there is very little work relating specifically to the use of visualisation at the construction stage. It also revealed considerable research in the use of visualisation as a presentation tool for clients or at the conceptual design stage. A considerable number of research reports and papers published in journals or presented at conferences were reviewed to build a firm basis for this research. The literature review on visualisation, design process, collaboration and communication provided a theoretical background and formed the basis for developing the survey questionnaire, the case studies and contributed to the development of the prototype system.

2. An industry survey was conducted by sending questionnaires to the top 100 UK contractors and consultants. The survey highlighted the problems faced by builders during the construction stage due to the lack of proper communication between them and designers.

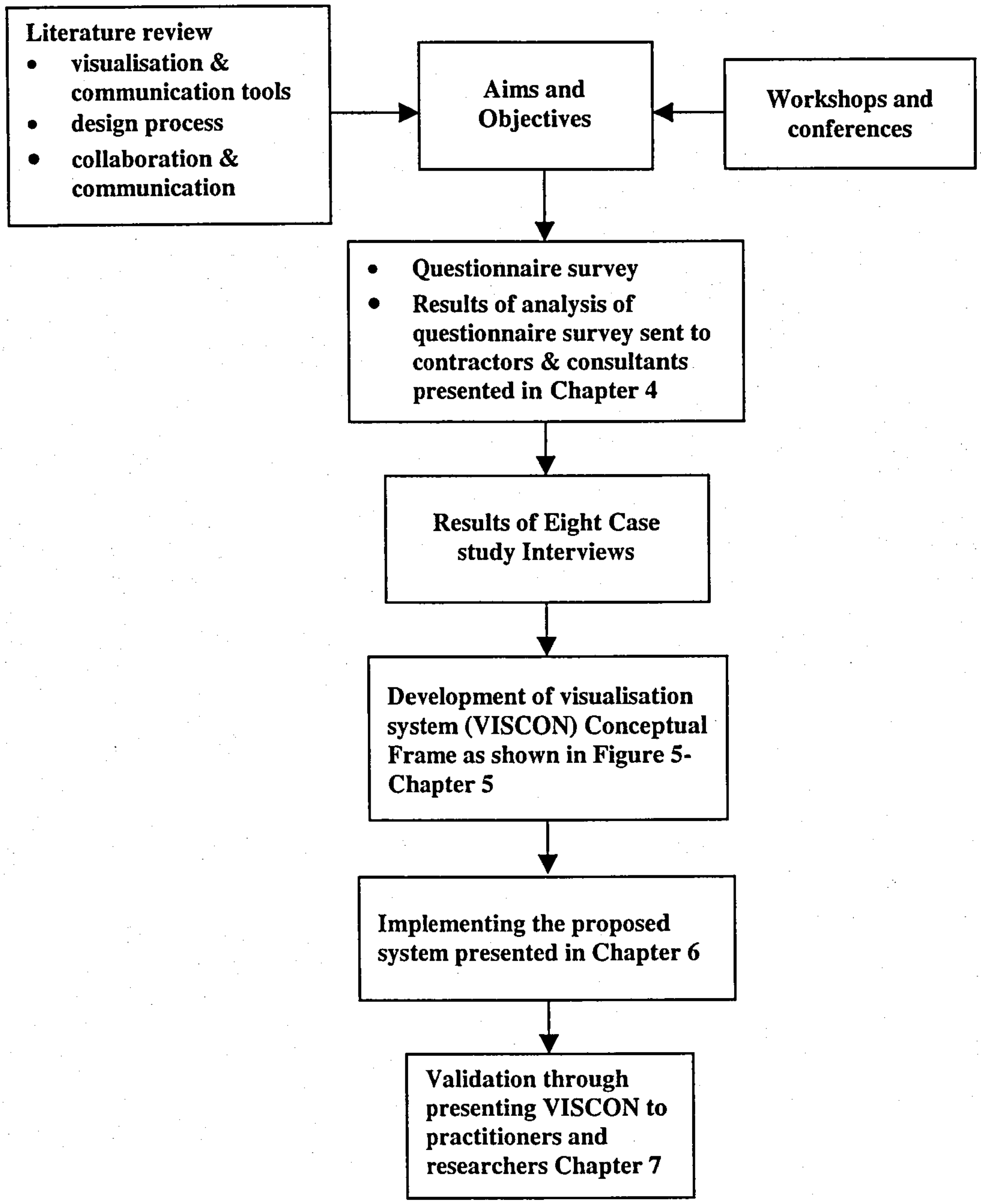


Figure 1-1 Research Scheme

3. Eight construction organisations (four construction companies and four design firms) were used as case studies. The main aim of these case studies was to investigate in depth the problems highlighted in the industry survey.

4. A prototype information visualisation and communication system was developed to meet the requirements of the construction industry as identified in the questionnaire survey and case studies.

5. The system was evaluated by researchers within the university and industry practitioners. The outcome of this was used to further refine the system.

Details of the methodology adopted in undertaking the above tasks are presented in Chapter Two.

1.6 ORGANISATION OF THE THESIS

This thesis is organised into eight chapters and set of appendices (see Figure 1-2). Brief summaries of the various chapters are provided below.

Chapter One is an introduction to the research. It provides a statement of problem, the aim and objectives of the research, and gives a preview of the research approach undertaken (i.e. the methodology).

Chapter Two discusses research methods available, and describes and justifies the methodologies used in the research.

Chapter Three reviews the current use of computer visualisation and communication tools in the construction industry. It also discusses buildability information and its communication.

Chapter Four presents the findings of an industry survey on information communication between designers and site teams. It is divided into two main sections: the first section describes the postal survey questionnaire and the second section describes the interview carried out with contractors and designers.

Chapter Five presents the architecture of the proposed system for the visualisation and communication of design information between design and site teams.

Chapter Six describes the prototype system demonstrator developed. Examples are used to illustrate how the system provides assistance to builders at the construction stage.

Chapter Seven summarises the results of the evaluation of the prototype model by researchers and industry practitioners. The chapter discusses the benefits and limitations of the system.

Chapter Eight presents conclusions from the work and suggests some directions for future research to bring about a greater awareness of the use of computer visualisation and communication tools support for site level activities. The chapter highlights the contributions to the research.

Appendices consist of additional information relevant to this research work. These comprise questionnaires, data outputs and a list of papers that resulted from this work.

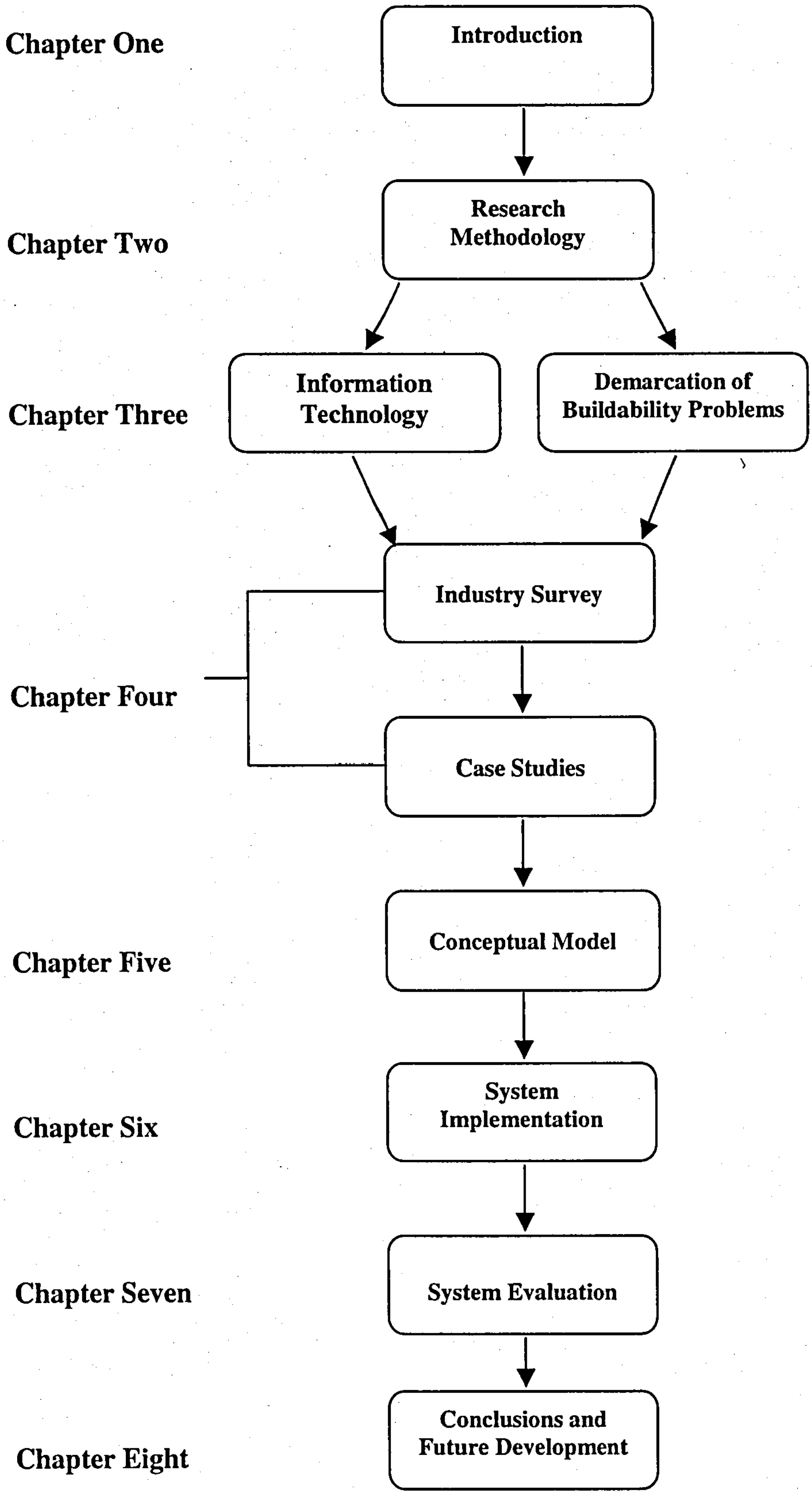


Figure 1-2 Layout of Thesis

Chapter Two
Research Methodology

CHAPTER TWO

2 RESEARCH METHODOLOGY

2.1 INTRODUCTION

This chapter gives an overview of the methodology used in the study. It represents a critical review of the major research methods used in the field of IT and construction management and justifies the choices that have been made in the selection of an appropriate research strategy. The first part of this chapter examines the underlying principles of the research process. These principles include various types of research; its context; the effects of knowledge, experience and bias; and the meaning of generalisation and particularisation in a research context. In addition, the chapter identifies various types of data, data collection and data analysis. The second part of this chapter presents the philosophical perspective of the research and methods chosen to achieve the research objectives.

2.2 PART I: THE UNDERLYING PRINCIPLES OF THE RESEARCH PROCESS

2.2.1 The Tools Available for Construction Research

Greenfield (1996) defines research as an art aided by skills of inquiry, experimental design, data collection, measurement and analysis, by interpretation and by presentation. In construction management generally, research attempts to answer real world questions relating to some aspects of acquiring, operating or disposing of constructed facilities (Stewart et al, 1996). A research method is a strategy of inquiring moves from the underlying philosophical assumptions to research design and data collection. It refers to principles and procedures of logical thought processes that are applicable to scientific investigation (Fellows & Liu, 1997). The choice of research method influences the way in which the researcher collects data. A specific research method should apply different skills, assumptions and research practices (Myers, 1997). Before discussing the chosen research methodology for this study, research methods in construction research are reviewed and their advantages and limitations are explained as they relate to this study.

The research methods which are most applicable to the construction are: action research, surveys, case studies, experiments, and ethnographic research (Fellows & Liu, 1997). In the following sections, each of these research methodologies are reviewed, although the final two methods (survey and case studies) will receive greater attention, as they are most important to this research study.

2.2.1.1 Action Research:

Action research is a vague concept but it has been defined as research that involves practical problem-solving which has theoretical relevance (Humford, 2001). Active involvement by the researcher is essential for identifying, promoting and evaluating problems and potential solutions (Fellows & Liu, 1997; Foster 1972). In addition, the roles of subject and researcher can easily be reversed at times during this type of research (Clark, 1972). Action research frequently uses a number of different methods for the collection of data; it also has a time dimension. A project using action research methodology may last for several years (Clark, 1972). It involves active participation by the researcher in the process under study. The researcher poses questions in order to identify, promote and evaluate problems and find potential solutions in relation to variables based on the responses presented (Dane, 1988; Fellows & Liu, 1997; Foster 1972). It usually involves not only gaining an understanding of the problem and generating ideas for improvement but also the practical application of these ideas in the field (Humford, 2001).

The advantages in using action research include very practical benefits that are likely to accrue to client organisations as a result and the fact that the researcher's bias is made overt in undertaking the research (White, 1985). In contrast, its applications are usually restricted to a single organisation. There are, therefore, problems arising from the generalisations of individual studies (Spencer & Dale, 1979). Other limitations of the action research method are different interpretations, and lack of control over individual variables resulting in difficulties when attempting to distinguish between cause and effect (Moore, 2000). Action research also places a great responsibility on the user of this method of research, who must be aware that in certain circumstances they could align themselves with a particular grouping whose objectives are at odds with other groupings (Coombs, 1999).

2.2.1.2 Experimental Research

Experimental research is best suited to known problems or issues where the variables involved are identified, or are, at least, hypothesised with some confidence (Fellows & Liu, 1997). There are two approaches to experimental research: laboratory experiments and field experiments.

Laboratory experiments are usually carried out to test relationships between identified variables, by holding all except one variable constant and then testing the effect on dependent variables by changing one independent variable. This is done with a view to making generalisable statements applicable to real world situations. The major strength of the laboratory experiment research method is the ability of the researcher to isolate and control a small number of variables that may then be studied in more depth. The major weakness of the laboratory experimental research approach is the limited extent to which the identified relationships exist in the real world (i.e. the scalability of the results).

Field experiments are an extension of laboratory experiments (Gallier, 1992), but are not conducted in a conventional laboratory. They are conducted in the real social, industrial, economic, political arena (Fellows & Liu, 1997). The strengths and weaknesses of field experiments are similar to those encountered in the laboratory experiment research approach, in addition is the difficulty in finding organisations or groups of people prepared to be experimented on. Furthermore, replication is problematic, in that it is very difficult to achieve sufficient control to enable replication of experiments with only study variable being altered.

2.2.1.3 Ethnographic Research

Ethnographic research in its broadest sense may be defined as the science of cultural description and is best accomplished by immersing oneself in the socio-cultural situation under study (Lang & Heiss, 1984). The ethnographic researcher becomes closely involved with the group that is under study, but with limited intrusion. This methodology is known as qualitative or phenomenological research. The researcher, using this research methodology, may need to spend a significant amount of time, sometimes months or even years, in the field to observe his/her subjects' behaviours, statements etc., in order to gain insight into what, how and/or why their patterns of behaviour occur (Fellows & Liu, 1997). Participant observation involves more than just recording and analysing participant's interaction; it also includes observer-participation and recognising the impact of the contextual variables surrounding the participants (Lang & Heiss, 1984).

Some researchers appear to turn to ethnographic research, as they are not satisfied with the restriction of traditional research techniques. These researchers consider this technique as a more innovative technique. As mentioned earlier, the ethnographic research approach allows the researcher to record subjects on their own terms, while the responses on a quantitative device, such as a scaled questionnaire, may be criticised in that they are biased or faked; this is often very difficult to dismiss (Lang & Heiss, 1984).

The strengths of ethnographic research methodology lie, in addition to what was mentioned earlier, in the creation of new ideas and insights. Its weakness arises from the unstructured, subjective nature of the process.

2.2.1.4 *Survey Research*

Survey research investigates a particular phenomenon by means of a questionnaire or interview (Leedy & Ormrod, 2001). Surveys are a good means of looking at a far greater number of variables than is possible with experimental research methods (Gallier, 1992). They can, therefore, provide a reasonably accurate description of real world situations from a variety of viewpoints. However, there is the possibility of bias on the part of respondents as well on the part of the researcher.

Survey research operates on the basis of statistical sampling and it is rarely possible to involve the full population. Statistical sampling is used to secure a representative sample as it saves money and time (Fellows & Liu, 1997), although other sampling methods are possible, e.g. theoretical sampling (Glaser & Strauss, 1967). The subject matter of the study must be introduced to the respondents. The researcher's task is to collect information relating to the variables, and based on data obtained, to examine the patterns of the relationship between the variables (Dane, 1988). Commonly, samples are surveyed through:

Questionnaire surveys: Questionnaires are a tool for soliciting and recording responses from individuals (Lang & Leiss, 1984). A questionnaire survey is a flexible research tool and can be used to gather information on almost any topic from any size or group of people (Moore, 2000). Questionnaires are useful research tools when:

a) a large sample or samples, perhaps even a population, need to be surveyed;

b) there is no essential need for face-to-face contact; and

c) the funds available for the research are limited.

Among the advantages of the questionnaire survey is accuracy, it is cheap, it gives access to dispersed respondents, and has a wide coverage of topics and respondents (Rothwell, 1983; Moore, 2000). Questionnaires can be designed to provide a degree of anonymity, or enable the researcher to follow-up certain points at later time.

Questionnaires are usually presented in a consistent format and style, and there is little scope for bias to be introduced by different researchers. The questionnaire is impersonal and avoids problems, which may develop during the interaction between an interviewer and the respondent. The questionnaire can also be completed in the respondent's own time, he/she can look through the whole questionnaire before giving his/her answer (Moore, 2000).

Possible disadvantages are expense, delay in receiving replies (Rothwell, 1993). Another disadvantage that questionnaires that they are sent to respondents who may be busy and end up passing them to someone who lacks the knowledge to answer the questions properly and therefore will not be able to provide the information required. In addition, the questionnaire survey lacks qualitative depth to the answers and may result in superficiality. It also allows for very little development or amendment as a result of lessons learned in the early stages of the research (Moore, 2000). This is why pilot surveys are recommended prior to the main survey.

Interviews: An interview is the collection of data through direct verbal interaction between the interviewer and the respondent. It is the appropriate research tool when: a) there is a desperate need for face-to-face contact(s); b) immediate responses are desirable; and c) its use is feasible – one deals with a relatively small sample, and there is adequate financial support, and availability of trained interviewers (Lang & Heiss, 1984).

Interviews vary in their nature and can be, structured; semi-structured; and unstructured (Fellows & Liu, 1997; Moore, 2000). The structured interviews are for large-scale interviewing and with no more than the questionnaire being administered in person. They require an interview schedule that needs to be designed in much the same way as a questionnaire. A semi-structured interview still places heavy reliance on the interview schedule. In unstructured interviews, the interviewer introduces the topic briefly and then records the replies of the respondents.

There are four ways of conducting interviews. These are as follows (Lang & Heiss, 1984):

1. Individual interview (one interviewer and one respondent);

2. Team interview (two or more interviewers and one respondent);

3. Group interview (group of people being interviewed by one or more interviewers);

4. Stress interview (respondent is placed in a stressful situation either physically and/or verbally, and his or her responses are observed "under fire").

One advantage of an interview over other research tools is the flexibility to deviate from the set pattern of questions if there is a need to probe areas of interest instead of relying on routine responses. It also provides more opportunity to obtain qualified answers. In addition, an interview offers greater communication between the interviewer and the respondent and allows for immediate checking of information. It provides the researcher with more control of the survey, making it possible to collect information at precise times. The interviewer has control over the flow and sequence of questions.

The drawbacks of interviews include the cost of interviewing in terms of money and time. The information obtained is often difficult to analyse, and there can be difficulty in ensuring a high degree of consistency in the presentation of the interview. There is also the problem of interviewer's bias.

2.2.1.5 Case studies

Case studies represent an intensive study of a phenomenon, using a variety of data sources and tools. The case study approach is problem-oriented and is applicable to an individual, a group of people, an institution, or a whole community (Lang & Heiss, 1984). It differs from action research in that the case study researcher seeks to study (organisational) phenomena and not to change them, unlike the action researcher who is often directly involved in planned organisational change (Avison et al, 2001).

A selection of case studies may be carried out on the basis of them being representative with similar conditions to those used in statistical sampling in order to achieve a representative sample to demonstrate particular facets of the topic or to show the spectrum of alternatives (Fellows & Liu, 1997). They are best used in studies that require deeper understanding of how and why things happen (Yin, 1984) rather than testing the relationships between them (Gordon & Langmaid, 1988).

A case study can be a scientific endeavour if it is conducted in line with the generally acceptable practice (Lang & Heiss, 1984). They can be exploratory, descriptive and/or explanatory (Yin, 1984). There are two uses for them. They can be used either to reduce the scale of the research study by focusing on a smaller number of units than would otherwise be involved, or to increase the range of different units within the study (Moore, 2000).

Case studies can be either single or multiple. The single case study is analogous to a single experiment, and many of the same conditions that justify a single experiment also justify a single case study. It is appropriate where the objective is to develop a new theory rather than to test, develop or prove an existing theory or to establish statistical generalisation. When there is more than one single case, the study has to use multiple-case studies. In this situation the terms (single and multiple case study) refer to the way in which the results of the study can be interpreted. In other words, what is the best way to consider the study either as serial (single) or parallel (multiple) designs.

Interviews with key actors in the subject under study is the most common way of conducting case studies. The interviews may be coupled with documentary data. The alternative method for conducting case studies is by individual or combined methods of ethnography, action research, interviews and documentation rather than a particular methodology for research (Fellows & Liu, 1997).

The strength of case study research lies in that the resources available for research are often limited, therefore providing the means of covering a large amount of ground for an acceptable cost (Fellows & Liu, 1997). In addition, case studies can provide a means of looking in-depth at complex problems. They also enable the researcher to compare a number of different approaches to the same problem in sufficient detail as to be able to draw out lessons which have general applicability (Moore, 2000). Case studies can also help in achieving greater realism in the research, and requires a reasonably holistic approach (Graham, 2000). In some situations they help to avoid reinventing the wheel and provide a necessary starting point where no other information exists upon which to base other forms of research methodology.

The weaknesses of case studies are that they are usually restricted to a single event or organisation. This means that it is difficult to get the same data from a sufficient number of similar organisations, therefore, it is difficult to generalise from case study research. They are often used for complex processes, their antecedents and outcomes; this process may last for months or years and the concerned people may not wait for publication of the research results and when they are published may become out-of-date. In addition, data collection and analysis process may be influenced by the researcher's characteristics and rely heavily on the researcher's interpretation of events, documents and interviews (Darke et al, 1998).

However, as mentioned above, weaknesses can be limited to some extent if particular attention is paid to them and if a careful rigorous methodological approach is adopted (Coombs, 1999; Moore, 2000).

2.2.2 Research Approaches

2.2.2.1 Quantitative Research

This type of research adopts scientific methods in which the initial study of theory and literature yields precise aims and objectives with the hypothesis to be tested. This approach seeks to gather factual data and study relationships between facts, and how such facts and relationships accord with theories and findings of any research executed previously (Fellows & Liu, 1997). Quantitative research depends primarily on a statistical database and analysis; therefore, it typically involves questionnaires and to a certain extent, highly structured interviews.

The quantitative approach essentially involves making measurements by collecting data. This approach builds upon developed principles, laws and theories from previous work to help decide data requirements of the particular research project. Quantitative research is the most commonly encountered as part of formal or conclusive research, but is also sometimes used when conducting exploratory research. The most common quantitative research techniques include: Observation technique, Experimentation and Survey technique. Quantitative research differs from qualitative research in the following ways:

- The data is usually gathered using more structured research instruments;
- The results provide less detail on behaviour, attitudes and motivation;
- The results are based on larger sample sizes that are representative of the population;
- The research can usually be replicated or repeated, given it high reliability;
- The analysis of the results is more objective.

2.2.2.2 Qualitative Research Approaches

Qualitative research involves the use of qualitative data, such as interviews, documents, and participant observation data, to understand and explain a phenomenon. It concerns developing concepts rather than applying pre-existing concepts (Wilson, 2000). Qualitative researchers can be found in many disciplines and fields, using a variety of approaches, methods and techniques (Myers, 1997). Qualitative research methods were developed in social sciences to enable researchers to study social and cultural phenomena. They may include action research, case study research and ethnography. Data sources include observations and participant observations (fieldwork), interviews and questionnaires, documents and texts, and the researcher's impressions and reactions.

There are three types of qualitative research: exploratory, descriptive and causal studies. Exploratory studies deal with identifying the real nature of research problems and for formulating relevant hypotheses for later tests. Descriptive research, by contrast with exploratory studies, is derived from prior knowledge. Causal studies attempt to identify factors underlying behaviour and to evaluate their relationships and interactions. Cause and effect relationships are very difficult to deal with in both a realistic and objective manner.

2.2.2.3 Combining Quantitative and Qualitative Research Approaches

The use of the two research approaches (qualitative and quantitative) reduces or eliminates the disadvantage of each. The combination results in a multi-dimensional view of the subject, gained through synergy. There are four possible research designs that employ both research approaches (Miles & Huberman, 2002):

- The first design involves both qualitative and quantitative data being collected at the same time.

- The second design uses a multi-wave survey, conducted in parallel with continuous fieldwork. The first survey wave may raise specific issues to which the researcher should pay specific attention. The later fieldwork results may then modify the way in which the second survey wave is conducted.

- The third design alternates the two methods, one after the other. The first stage employs exploratory qualitative data collection that leads to the adoption of a quantitative data instrument such as a questionnaire. The questionnaire results can be studied in more detail in a further round of qualitative research.

- Finally, the fourth design also uses an alternating style but in a slightly different way. First a survey is conducted to point the researcher to a specific phenomenon. Using qualitative research, the researcher develops a strong close-up conceptual understanding of the relationship between things and how they work, and the quantitative experiment is designed to test the resulting hypotheses. The combination of more than one research methodology in a single study is best understood, then, as a strategy that adds rigor, breadth, complexity, richness, and depth to any inquiry (Denzin & Lincoln, 2000; Moore, 2000).

The decision of whether to choose a quantitative or a qualitative design is a philosophical one. While some of these appear to be opposites, it should be kept in consideration that these are two different philosophies, which themselves are not necessarily polar opposites. Table 2-1 shows the comparison between qualitative and quantitative research methods.

Although most researchers do either quantitative or qualitative research work, some researchers have suggested combining two or more research methods in one study (known as triangulation), to investigate the problem (Fellows & Liu, 1997). There are three meanings or models of triangulation (Fielding & Schreier, 2001):

1. *Validity model*: triangulation is the mutual validation of results obtained on the basis of different methods.
2. *Complementary model:* triangulation is the means toward obtaining a large, more complete picture of the phenomenon under study;
3. *Trigonometry model:* triangulation in its original trigonometrical sense, indicating that a combination of methods is necessary to gain any (not necessarily a fuller) picture of the relevant phenomenon at all.

Generally triangulation reflects an attempt to secure an in-depth understanding of the phenomenon in question. It is usually adopted in research to clarify meaning, verifying the repeatability of an observation or interpretation (Stake, 2000). Research

Table 2-1 Comparison between Qualitative and Quantitative Research

(Source: Burns & Grove (1993); Streubert and Carpenter (1995); and Naoum, (1998))

Qualitative	Quantitative
Subjective	Objective
Soft science	Hard science
Literature review may be done as study progresses or afterwards	Literature review may be done early in study
Develops theory	Tests theory
Multiple realities: focus is complex and broad	One reality: focus is concise and narrow
Discovery, description, understanding, shared interpretation	Reduction, control, precision
Interpretative	Measurable
Organismic: whole is greater than the parts	Mechanistic: parts equal the whole
Reports rich narrative, individual interpretation	Reports statistical analysis
Basic element of analysis is words/ideas	Basic element of analysis is numbers
Research is part of process	Researcher is separate
Participants	Subjects
Context-dependent	Context-free

Table 2-1 Comparison between Qualitative and Quantitative Research (Continued).
(Source: Burns & Grove (1993); Streubert and Carpenter (1995); and Naoum, (1998))

Qualitative	Quantitative
Research questions	Hypotheses
Reasoning is dialectic & inductive	Reasoning is logistic & deductive
Describes meaning, discovery	Establishes relationships, causation
Uses communication and observation	Uses instruments
Strives for uniqueness	Strives for generalisation
Designs: phenomenological, grounded theory, ethnographic,	Designs: descriptive, correlational, quasi-experimental,
Sample size is not a concern; seeks "information rich" sample	Sample size 30 to 500
Provides information as to "which beans are worth counting"	Counts the beans
Scope of finding is Idiographic	Scope of is nomothetic
Relation ship between researcher and subject is close	Relation ship between researcher and subject is distant
The role is attitude measurement based on opinions and views	The role is fact-finding based on evidence or records
Nature of data is rich and deep	Nature of data is hard and reliable

triangulation helps the researcher to eliminate bias in data collection (Creswell, 1994). This research style assumes that any bias inherent in particular data sources, investigation and methods can be neutralised when used in conjunction with other data collection methods. Creswell (1994) cites several illustrations of triangulation in the literature where researchers combine qualitative and quantitative data sources. These include observations supplemented with structured, quantitative observations and survey research combined with qualitative interviews. Green et al (1988) argue that triangulation allows researchers to seek convergence of their results through overlapping data sources. Moreover, triangulation of methods adds scope and breadth to a study by allowing the researcher to observe the empirical evidence in different ways. Finally, the use of multiple sources of evidence can be used to support the construct validity of the research design (Yin, 1984; Morse, 1991). Within research, there are two major schools of thought. The first school includes those who advocate the use of quantitative approaches, such as statistical methods while the other comprises those who support the use of the more humanistic and qualitative alternative. Between these two extremes of methodologies (Figure 2-1), management

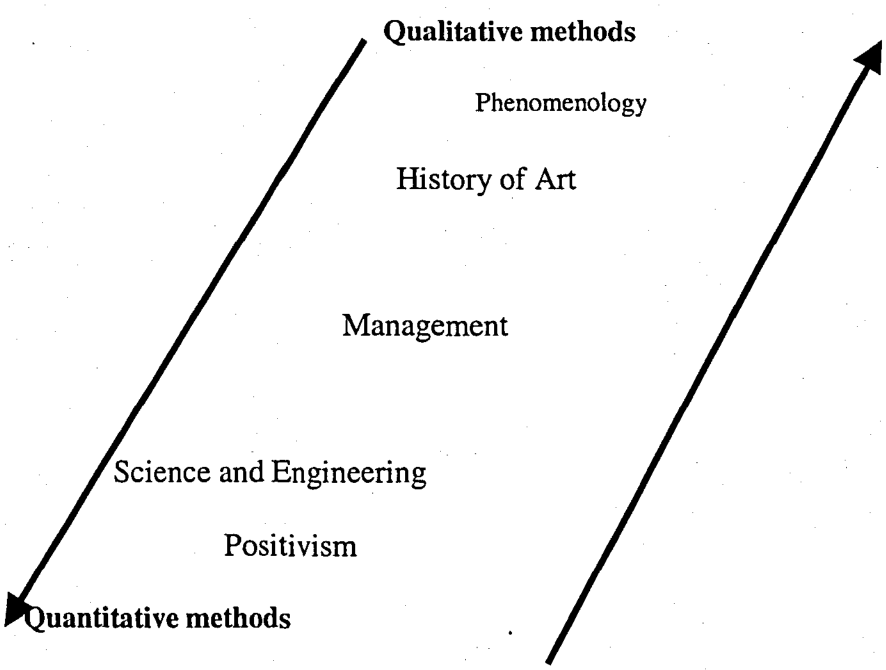


Figure 2-1 Research philosophies for different academic disciplines
(Source: Edum-Fotwe et al, 1996)

research can be defined, which can inform construction management, and this indicates the need to address research within a multi-disciplinary framework (Edum-Fotwe et al. 1996). Whatever style or approach of research is chosen, the most important is the understanding and appreciation of validity and applicability of results and conclusions (Fellows & Liu, 1997).

2.2.3 Research in construction IT

The construction industry is characterised as information intensive. The creation, communication and co-ordination of the huge amount of data is an inevitable industry problem and industry people are seeking ways to use computers to overcome this (Leslie, 1996, Construct IT, 1995). Research in construction IT differs from the study of IT as a purely technical phenomenon (Whyte, 2000). However, researchers in IT are not in the same situation as natural scientists (Crook et al., 1996). Researching complex socio-technical phenomena is unlike scientific research in which the objects of the study are non-conscious, neither knowing nor caring about the fact they are the subjects of research, nor about the presence of the researcher. In socio-technical research, the researcher must make use of the socially-gained abilities to make sense of the world around them to understand what the people who are subjects of the research tell them, as those subjects themselves (Crook et al, 1996). Researchers see only the positive side of hard methodology approaches without taking into consideration the complexity of IT applications. They concentrate their research on technical aspects forgetting how IT can be accepted and used by construction practitioners who are hesitating in adopting new technology (Leslie, 1996).

2.3 PART II: RESEARCH STRATEGY TAKEN FOR THE RESEARCH

According to Creswell (1994) the guiding principles for the development of any research methodology is that it must completely address the research questions. To meet these objectives, a research study should have a detailed research design that can be used as a blueprint for collecting observations and data that are connected to the research questions. Simister (1995) stated that the research design should:

- Make explicit the questions the research should answer;
- Provide hypothesis/ propositions about these questions;
- Develop a data collection methodology; and
- Discuss the data in relation to initial research questions and hypothesis/ propositions.

2.3.1 Research Strategy

Deciding on which type of research to follow depends on the purpose of the study and type and availability of information which is required (Naoum, 1998). As mentioned earlier in this chapter, research in construction management needs to be addressed within a multi-disciplinary framework (Edum-Fotwe et al. 1996). Consequently, it was decided that the most effective research approach for this study was to combine qualitative and quantitative methods. This would produce findings that enable a convincing demonstration of the potential use of computer visualisation as a communication tool for information and collaboration during the construction stage of a building. The activities in the methodology were designed to investigate the current use of computer visualisation and communication to solve problems that arise during the construction stage of a building or facility. Furthermore, it was considered that a combined research approach would enable the findings from each stage of the project to inform and refine subsequent stages, consequently enhancing the reliability and validity of the research and ensuring that the focus of the study was maintained throughout the research life.

2.3.2 Research Methods Used

According to Phillips and Pugh (2000) and Bourner (1996) the important characteristics of any research are that it is based on an open system of thought, researchers examine data critically and they generalise and specify the limit of their generalisations. According to both authors there are four elements to form a PhD:

- *Reviewing the field* by conducting a literature survey in the field of study;
- *Theory building* describes what the research is about and why it is done;
- *Theory testing* justifies the relevance and validity of the proposed solution of the research;
- *The reflection and integration* evaluate the importance of contribution made to the discipline by research.

In pursuance of the first three objectives as stipulated earlier in Chapter 1, the research has gone through several stages. This research study has tried to apply the above guidelines to achieve its aim and objectives. Surveys and action research have been used in this study to investigate the general research problems. The methods used to achieve the aim and objectives of this research stated in Chapter 1 section 1.3 are:

2.3.2.1 Literature Review

Theory generation and testing have been carried out in an iterative manner throughout the life of the project and a contextual approach has been taken. The Literature review is regarded as an essential stage in conducting a research project, as it amounts on average, to between 20 and 25 per cent of a thesis content (Naoum, 1989). It can help the researcher in delimiting the problem under investigation, introduce him/her to new approaches towards solving his/her problem; help him/her avoid errors in planning his/her study; suggest new ideas to him/her; and acquaint the researcher with new sources of data (Lang & Heiss, 1984). With the initial literature review, seminars and conferences attended in the early part of the research helped in defining the broad aim and objectives of this research, which where refined over the research period to those presented in Chapter 1. A literature survey was undertaken to investigate various issues relating to design information and its representation tools; computer visualisation and communication tools; buildability and problems that relate to the detail design information; and collaboration during design and construction stages of a project. Chapter 3 presents the main findings of the literature survey.

2.3.2.2 Surveys (Data Collection)

As mentioned earlier, two primary methods have been widely used for data collection, these are postal questionnaire and interview methods. In this study, both methods were used in order to obtain representative information and a high response rate.

Postal Questionnaire

A survey was used as the method for collecting data to establish a general industry-wide perspective on the role of visualisation in buildability. A postal questionnaire was considered appropriate for the investigation, as the total population of organisations involved is reasonably high (100). The survey had the following aims:

1. To assess the current usage of computer visualisation and communication tools by construction industry professionals;

2. To assess the current infrastructure for computer visualisation in the construction industry;

3. To identify buildability problems (their nature and causes) to establish how information related to buildability is communicated and exchanged, and to identify and evaluate the media used to carry out these processes; and

4. To examine the level of collaboration between design and construction teams in solving problems that arise during the construction process of a project.

The postal survey questionnaire is a self-completion form designed to gather information from individuals located in different area of the country. The questionnaire was sent to project managers in construction and design practices.

An important aspect of designing any questionnaire is to ensure the largest possible return, which enables meaningful analysis. It must also provide a wide coverage pertaining to the subject of investigation. The success of questionnaire surveys depends on how effectively the instrument can be handled. The accuracy of the data collected largely depends on the questions asked as well as how respondents perceive them. The questionnaire design was based on an extensive review of the literature dealing with information visualisation and communication in the construction industry. Figure 2-2 depicts the process described in developing the questionnaire. During the design of the questionnaire, two main considerations were kept in mind: the limited time of the respondents and their heavy schedule. The design of the questionnaire was done using procedures recommended by Prescott (1993), Hoinlville et al (1985), and Fowler (1993). These recommendations include the following:

- The questions must be clear, not ambiguous and easy to answer;
- The questionnaire should be designed attractively and should be uncluttered;
- The questions should be in short sentences and brief;
- The language used for writing the questions should be simple;
- Biased terms should be avoided in order to get a real view from the respondents; and
- The questionnaire must be designed in such a way that the analysis of results is easy.

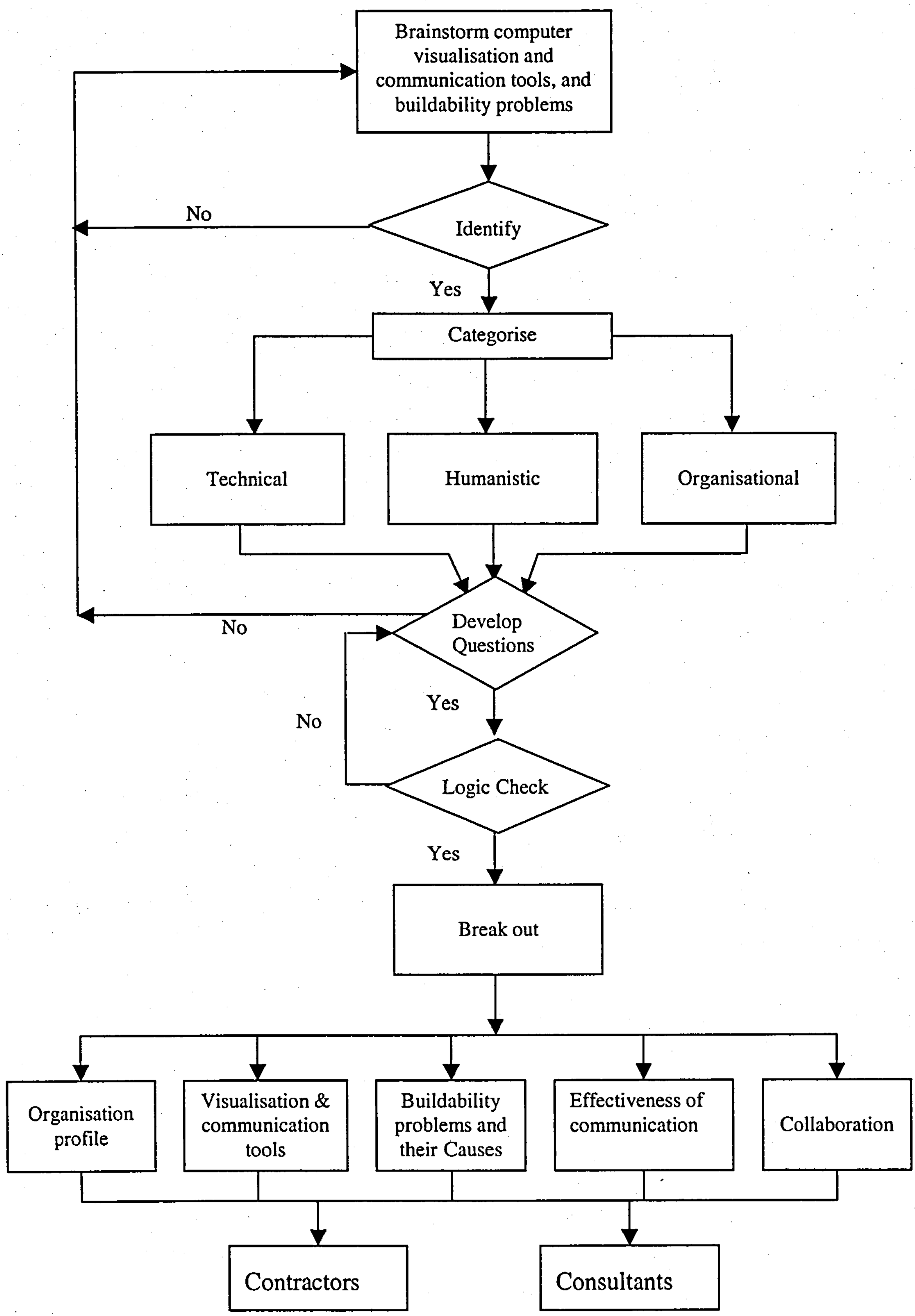


Figure 2-2 Questionnaire Development Process

Fowler (1993) advised that when a self-administered questionnaire is used, it is better to have closed questions. Grid closed questions (those for which a list of acceptable answers was provided to the respondents, normally by ticking one box or rating scale). In some questions, a space was provided as an option for respondents to give additional information. A space was given at the end of the questionnaire for respondents to add any relevant information they might think important.

The questionnaire was designed so that:

- The questionnaire involved clear guidance to respondents wherever appropriate the answer to each question.
- Questions with similar content were kept together;
- Questions were as consistent in style as possible; and
- Enough space was provided for the respondents to express their views and record their comments.

Pilot questionnaires surveys are recommended in questionnaire design. A pilot survey is a trial run for the data collection strategy using a small sample of the targeted population. Its objective is to identify unclear questions and provide preliminary test of validity and reliability of the collected data. After the initial literature review, two near 'mirror-image' questionnaires (one for contractors and the other for designers) were developed, pilot tested and sent to industry practitioners. The objectives of the pilot study were to ensure that adequate time and careful thought were expended in wording of the questions as well as testing the appropriateness of data the collection instrument prior to sending it to a large number of respondents. Chapter 4 describes in more detail the pilot survey conducted .

A cover sheet was included with each questionnaire to provide the respondents with:

- Brief introduction to the research;
- Purpose of the study;
- Assurance that the information provided will be held in strict confidence; and
- An affirmation that the analysis of the results would be sent if so requested.

A copy of the covering letter attached to the postal survey questionnaire is presented in Appendix A.

The data collected from the postal survey were analysed using descriptive statistics method, which provides a general overview of the results. The software used to analyse questionnaire responses was Microsoft Excel with the use of tabulation, bar chart or pie chart methods. For ease of categorisation shading and patterning were used together with writing on the chart and legend style below the chart. Responses to questions are analysed and presented in the first section of Chapter Four.

Case Studies

As postal surveys gather empirical data that can be generalised to a wider community but provide little insight into the processes behind the phenomenon under study, the questionnaire surveys were followed by semi-structured interviews. These semi-structured interviews were conducted in order to obtain a deeper understanding of the problems found from the analysis of the questionnaire survey. Semi-structured interviews have been chosen as they allow the interviewer more freedom to probe various areas and to raise specific queries during the course of the interview (Naoum, 1998). Their aims are to:

1. obtain more information on issues that arise from the analysis of the postal questionnaire;

2. find examples of buildability problems that may be used in the prototypes; and

3. investigate whether buildability problems are the same in most projects or differ from one project to another.

After the objectives of the interviews were clarified, a list of questions were prepared and discussed with a number of researchers. Having the questions ready, a letter was sent to project managers to grant access. The letter was attached with a list of the main questions that would be discussed during the interview. After a few weeks, follow up phone calls were made to the selected interviewees to fix the date and time for the interview.

The interviewer gave a brief statement to describe the objectives of the interview and indicate that the information provided will be treated in confidence. Each interview was conducted on a one to one basis. After granting permission from the interviewee, the interviews were recorded so that the interviewer could concentrate on the discussion. In order to get reliable information from interviewees the following tactics were used as appropriate (Marginson, 1996):

1. Stating to the interviewees that the researcher does not have a specific theory to prove or disprove, and thus interviewees are not meant to provide the 'right answer';

2. Asking the interviewees to give examples, whenever possible, to illustrate the issues they are describing;

3. Asking the interviewees to explain how they know that what they say is true;

4. When there is contradiction or inconsistency with prior remarks or statements, the researcher inquired in a way that sought to communicate the absence of a value judgement on his behalf;

5. In some cases, the researcher rephrased the interviewee's answer to test whether it was understood correctly and accurately.

Semi-structured interviews were used in this research study as they allow the broad nature of the investigation to be maintained but also provide the opportunity to capture specific issues that may help the researcher to fully understand the phenomena under investigation. They also allow the interviewer to be guided by the perceptions and interests of the interviewee while maintaining a level of comparability between interviewees.

The interviews were transcribed in detail, but they were not sent back to the interviewer because the questions were straightforward, the data collected were not sensitive, and the system which will be developed is not for interviewees only but for general use. The second section of Chapter 4 describes the main findings from each interview.

2.3.2.3 Prototype Development

Research can be generally divided into work which discovers and describes existing reality (explorative research) or which aims at creating a new reality (e.g. new technology or processes) that needs to be evaluated and justified. The research described in this thesis aimed at developing a visualisation and communication system that can be used in the construction industry to communicate design information and support collaboration between design and construction teams during the construction stage of a facility. An important element of the methodology used in this research is prototyping, which includes conceptualisation. In this study, prototyping is used as an approach to demonstrate the use of different types of computer visualisation as a communication medium to transfer design information during the construction stage. A framework has been developed for the flow of information related to buildability between design and construction teams during the construction stage of a facility. The validity of the theories in practice was tried in two different case studies. The prototypes were planned and implemented, this is described in Chapters 5 & 6.

2.3.2.4 Evaluation of the Prototypes

The research evaluation means analysing the applicability of the prototypes. The system developed has been presented to researchers and construction professionals and an assessment was conducted using a questionnaire completed by potential users at the end of the presentation. The preliminary prototypes were evaluated and some modifications made to make the system more efficient and practical taking into account the feedback from potential users. The research evaluation is described in detail in Chapter 7.

2.4 SUMMARY

This chapter was divided into two main sections. The first section reviewed the research strategies and methods available for research in construction management. The second section outlined the research strategy and methods used to address the aim and objectives of the research. This research study adopted a combination of research methods (qualitative and quantitative research approaches).

The next chapter describes the results of the literature survey for theory development. It gives a description of visualisation and communication tools used within the construction industry. Buildability and collaboration to solve problems that may arise during construction stage of a facility are also discussed.

Chapter Three
Information Visualisation and communication

CHAPTER THREE

3 INFORMATION VISUALISATION AND COMMUNICATION

3.1 INTRODUCTION

The first chapter introduced the research problem. It described the background and justification for the research topic and summarised the research objectives, methodology and major achievements. The second chapter reviewed the methodologies used in construction research and discussed the methodology adopted in this work.

This chapter reviews computer visualisation and communication tools and concepts in order to assess their suitability for the support of site level operations. It covers the design process and related information; computer generated visualisation; it also covers communication and collaboration in the construction industry.

3.2 CHARACTRISTICS OF THE CONSTRUCTION INDUSTRY

The building construction industry is characterised by a dispersed organisational structure in which there is a number of different groups of skilled participants in the planning, design and construction of a building project (Fenves et al., 1994). These groups of participants include the client, architect, structural engineer, mechanical engineers, contractor, and sub-contractors. These have different capabilities and experiences (Kalay, 1998) and each discipline has its own terminology and tools for defining and using different types of information (Zamanian & Pittman, 1999; Rosenman & Gero, 1997). However, these groups have one objective, that their work has to be co-ordinated in a such way as to meet the clients' objectives in respect of such matters as function, size, performance and quality (Bennett, 1985).

Buildings are complex in nature. The size of the product to be designed is one that causes the most complexity. Multiple systems that compose a building often show significant complexity themselves and require the maintenance of many relationships and dependencies within and between them. These systems are often the responsibility of different disciplines and participants, which increases the complexity of the planning, communication, ownership, etc. (Mokhtar et al., 1997; Leeuwen, 1999). The one-off nature of the product further complicates the above issues as the teams of participants are assembled for every project. Therefore, conventions between participants are not easily formulated over longer periods of time. According to Fenves et al. (1994) building design and construction is characterised by:

1. The fact that It involves professionals from many different disciplines representing a specialisation that is often not understood by others. These disciplines include architects, structural and mechanical engineers, developers etc.

2. Each discipline looks at the design and construction of the building from a different perspective.

3. Communication between the different disciplines takes place in two ways; either verbal or through blueprints and written documentation. These are sometimes inadequate and limit the information exchange between disciplines to just a description of the solution. Information only includes what is required by the contractor to construct the building. Other information such as intermediate decisions and design rationale are not communicated.

4. The use of hardware and software by each organisation is based on their own needs, which may not be compatible with other organisations. The transfer of data is still difficult in spite of standardisation efforts.

3.3 THE DESIGN AND CONSTRUCTION PROCESS

Design is no longer regarded as the product of the talented individual but rather as the collective achievement of different disciplines with different qualifications (Kalay, 1998). A successful design is a testament of teamwork and co-operation (Fenves et al., 1994).

Traditionally, the design develops in a sequence from the architect to the engineers. The design starts with the client's brief; the architect then produces an architectural concept. This is passed on to the structural engineer to carry out the structural design. The structural designer passes the conceptual design with his structural input to the electrical and mechanical services engineers to develop their part of the design. The quantity surveyor produces the bills of quantities and cost plan. The final design with the bills of quantities and cost plan is passed to the contractor who takes responsibility for the construction of the proposed facility. This process is characterised by the over walls' syndrome (Figure 3-1) and can lead to difficulties; these include (Evbuomwan and Anumba 1998):

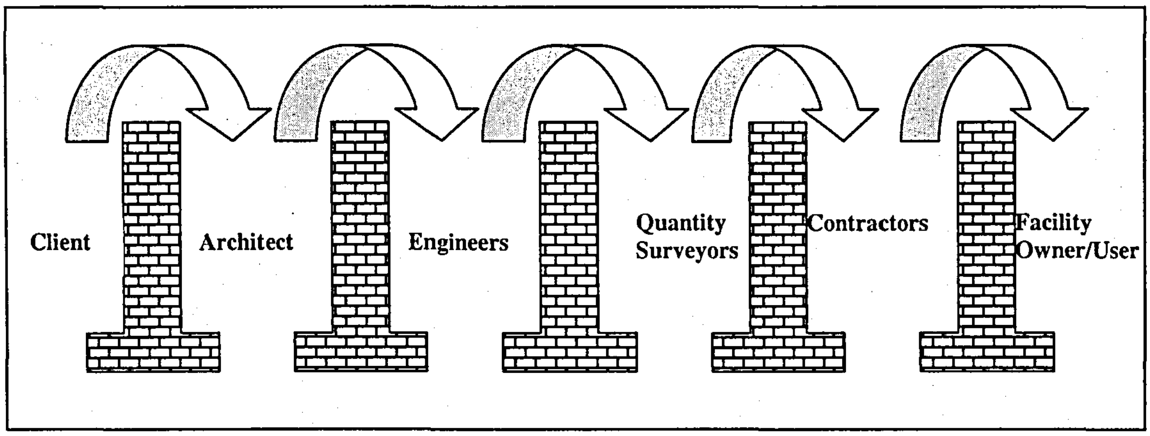


Figure 3-1: Sequential 'over-the-wall' syndrome in construction (Evbuomwan and Anumba, 1996)

- Communication between members of the design team is poor;

- Whole life-cycle analysis of the design is usually not conducted;
- Design changes are frequent, and responsibilities are not well defined; and
- Design and construction information are fragmented.

A complex design project requires the participation of a number of design disciplines bringing together different knowledge and expertise to the overall effort. As the project gets larger, the number of individual disciplines increases, and each individual discipline is represented by several design professionals. Each of these design professionals brings specific knowledge and experience to the design. The goal of collaborative design is to combine all the different groups' knowledge, experiences, and perspectives, towards achieving the global design objectives (Fenves et al., 1994).

Fenves et al. (1994) outlined a set of criteria for a successful design. This should be:

1. *Feasible:* contributions from participants must be consistent with one another and with external restrictions and constraints such as regulations codes of practice, budget limits etc.

2. *Effective:* the design should be effective with respect to global objectives, of the proposed project such as minimisation of construction cost, maximisation of aesthetic appeal, etc.

3. *Efficient:* revisions and iterations to the design, when they occur, should be easy to deal with in an efficient and harmonious way.

3.4 NEW FORM OF PROCUREMENT

There is a constant pressure in the construction industry to reduce project delivery times and project development costs, despite the increased complexities and risks involved in many of today's construction projects. Many construction techniques and methods have been researched and applied with varying degrees of success. However, there is an industry wide perception that there is still some room for improvement. New forms of procurement were introduced to achieve a high level of deign-construction integration. The following describes in brief the new forms of procurement (Shen & Walker, 2001).

Design and Build, for example, has gained popularity over other methods because it allows complex projects to be completed in less time and save costs along the way. In a survey of 52 construction firms in the UK (Akintoye, 1994), factors contributing to the reduction of construction time for design and construct compared with traditionally procured projects were summarised as follows:

- Incorporation of design process into the construction programme;
- Integration of design and construction;
- Speed of response to alterations-design changes can often be more smoothly accommodated;
- Better rationalization of design detailing;
- Better solution prior to activity on site minimising abortive work;
- Short cuts available to designer/builder;
- Less parties involved in design;
- Motivational benefit from the design and construction teams being on the same side.

Many of the keys to success in all Design and Build projects is flow of information (Shen & Walker, 2001). The Design and Build process involves design, costing, and scheduling taking place concurrently. These concurrent functions allow the most informed decisions to be made by the owner and all team members.

The need for greater integration within the construction industry has led to the adoption of various concepts from other industries. One of these, which offers major scope for effective co-ordination and integration within the construction industry, is Concurrent Engineering (Kamara et al, 2000).

Concurrent Engineering is a product development approach that has been used for many years in the manufacturing industry. It has had great success in shortening project delivery times and in reducing development costs. Concurrent Engineering is a departure from the traditional sequential approach to product development and thus requires a new design environment and technology in order to support the extensive interdisciplinary co-operation and integration inherent in the concurrent approach. Concurrent Engineering can be defined as " a systematic approach to the integrated, Concurrent design of products and their related processes, including manufacturing and support (Winner et al, 1988).

Only recently have efforts been made to integrate Concurrent Engineering to the construction industry. Researchers believe that Concurrent Construction may hold the key to achieve faster project delivery times while at the same time reducing the costs of development (Prasad 1996). Concurrent Construction is based on division of the project into manageable parts assigned to a multidisciplinary project development team, who carries out the delivery of the specific part in an integrated fashion in a single phase (Anumba et al, 2000b).

The Private Finance Initiative (PFI) was launched in 1992 (Blackwell, 2000; Gladwin, 2002). It introduced a new means of procurement for the public sector to deliver higher quality more cost-effective public services. Under traditional methods, public bodies purchase capital assets such as roads, hospitals or IT hardware and software and operated these themselves. Under the PFI, the public sector enters into a contract for the delivery of specified services with the private sector which designs, builds, finances and operates (DBFO) the assets required.

PFI differs from traditional procurement methods in several ways. With traditional method of procurement, if a new hospital was to be built, for example, the local authority would normally organise the design of the building and construction financed from public sector funds. The contract to build the hospital would be tendered out on a competitive basis and the winning bid would normally be the lowest price put forward. The contractor would build the hospital and upon completion hand the asset over to the authority which would then assume responsibility for maintaining, running and operating the hospital.

If a hospital is procured on PFI basis the following happens: the authority sets its Outline Business Case (OBC) to invite consortia to bid for the design, funding, building and operation of the hospital on a concession basis. The winning consortium will have full control over the design and construction of the building and upon completion of the construction, will be responsible for the operation of the hospital providing a variety of ancillary services such as portering services and other facility management services.

The PFI is expected to lead to greater private sector ownership and more private sector involvement in the operation of assets, since many of the value for money gains in PFI projects are likely to come from the benefits of combining asset design, construction, on-going operation and maintenance (and possibly refurbishment and/or replacement).

3.5 DESIGN CO-ORDINATION

As mentioned above, complex building projects are assemblies of many different systems, each system has particular characteristics, and a different function. In spite of the building design being multi-disciplinary, decisions influencing the design of components of various systems of a building have to be made collaboratively. In other words a decision by a specialist about a specific concept of the design can depend on other decisions by another specialist. For example, decision by the air conditioning specialist to size the ventilation duct depends on the function of the space, the function of the space is influenced by the architect. Therefore design changes made in one discipline often has an impact on other disciplines (Krishnamurthy & Law, 1996).

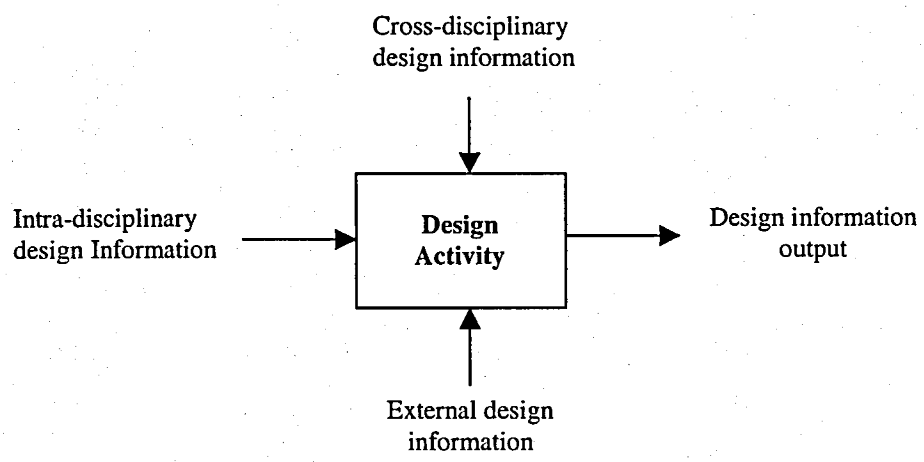
Each subsystem is designed separately and then combined together with the other components. This process is carried out to identify any conflicts between different design components. These conflicts might not be discovered until most of the design work is completed leading to costly changes and possibly poor quality, and client dissatisfaction (Mokhtar et al., 1997).

Several researchers have tried to address the complexity of the design process by dividing the tasks assigned to different design groups. Luiten and Tolman (1997) tried to improve integration, i.e., the continuous and interdisciplinary sharing of data, knowledge and goals among all project participants. Others made attempts to develop models for easy storage, retrieval, and modification of building data (Ray-Jones & McCann, 1971; Birgerson, 1967). Accordingly, Meager (1973) developed the HARNESS prototype system, Eastman (1980) developed the GLIDE prototype system, and Hoskins (1973) developed the BDS prototype system. However, these systems have not had a major impact on the practice of building design and are not intended to be used for buildability purposes. They have also been characterised as being complex as they required advanced and highly complex commands and control elements to effectively integrate the system segments (Eastman, 1992). An information model has been developed by Hegazy et al (2001) to store design information, record design rationale, and manage design changes to ensure a consistent and well co-ordinated design.

3.6 PROJECT INFORMATION

Design includes a process of problem solving. This means that it involves activities such collecting, analysing and generating information (see Figure 3-2). The output of a design activity is the definition and the specification of a solution (Leeuwen, 1999).

The information generated can be written, graphical and numerical documents. The information that is searched and communicated during the construction stage of a project can be substantial and can include drawings, specification, calculations and



schedules.

Figure 3-2: Information process during design stage (Hammond et al., 2000)

Drawing primitives (lines, circles, etc.) are widely acceptable in the construction industry as they can be read and interpreted by anyone with little or no training. On the other hand, the inherent fuzziness of drawings and their intent and format can lead to ambiguous interpretations. This usually leads to the need for requests for information and face-to-face meetings to clarify some of the information contained in them. Communication on ambiguous or ill-defined information requires the use of rich and interactive media such as 3-D, VR, VRML, animations (Pietroforte, 1997).

Information is the life-blood of a construction project (Atkin, 1995). It covers drawings, specifications, bills of quantities, schedules, financial statements, contract agreements etc. These different types of information must be shared by many people and organisations. A classification of project information is necessary to facilitate its transfer between these different participants in the design and construction of a project.

3.6.1 Types of Information

Project information can be categorised into (see Figure3-4) technical, commercial, and managerial and control information (Construct IT, 1995; Atkin, 1995):

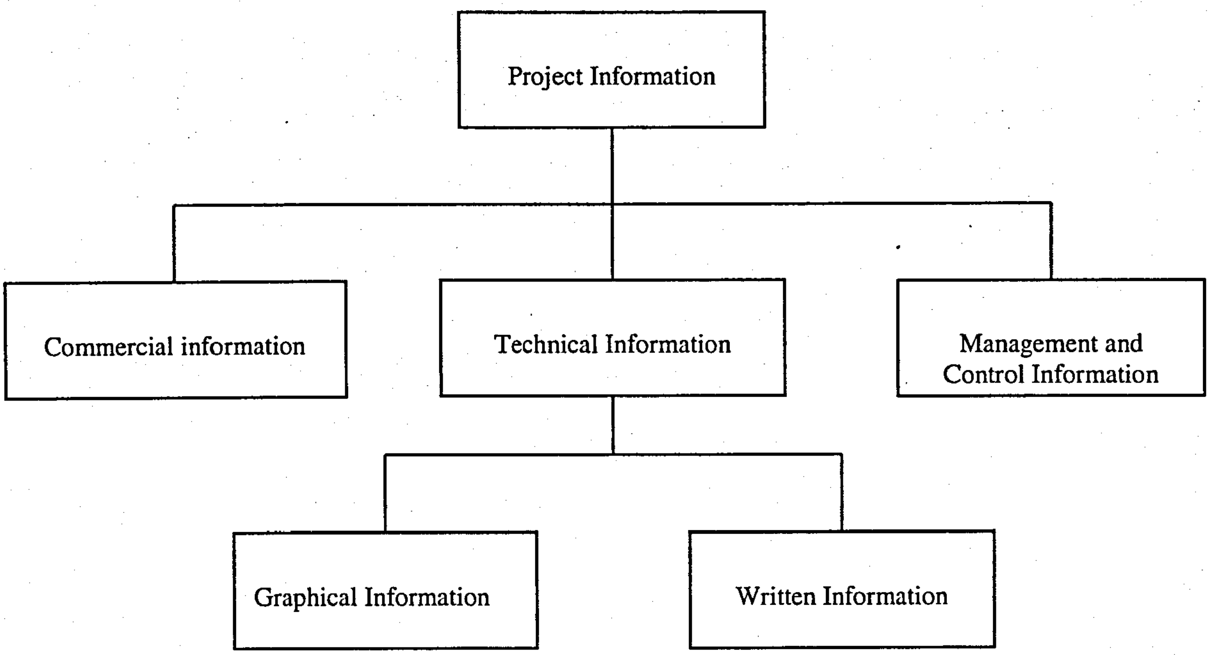


Figure 3-3: Information types in construction (construct IT, 1995)

Technical Information: is information that describes the geometry of a building and its technical content. This type of information can be divided into two main categories, graphical and written information.

Commercial information: establishes the responsibilities of each participant in a project for the delivery of the final product. It includes delivery schedules, costs, payment schedules, terms and condition of the contract.

Managerial and control information: includes all information required to monitor the project, generation of reports, etc.

3.6.2 Representing Design Information

A whole range of representation techniques for designs has been developed. The invention of the mathematical perspective by Brunelleschi and Alberti moved representational techniques forward significantly (Groak, 2001). Projective geometry, or mechanical drawings of third-angle projection was invented by Casper Monge who worked in Napoleon's army. This technique was originally used to design fortifications, and enabled people to predict where objects would be in three-dimensional space; it remains the main basis of most production drawing in the building industry (Groak, 2001).

Drawings are the main medium designers use to convey their intent to everyone involved in a building project. They are divided into location drawings, assembly drawings, and component drawings (Thompson, 1999):

<u>Location drawings</u>: these show where the project will be but may not show how the work will be performed. They give an overall impression of the building and provide key data to position the whole building. Location drawings also locate spaces and parts such as windows and doors. These drawings also give a key as to where more detailed information can be obtained.

<u>Assembly drawings</u>: show how the building is put together on-site and generally provide more detailed information on the construction of the building. They contain details of, junctions between a floor and a wall or between a roof and a wall.

<u>Component drawings</u>: show details of items manufactured on-site and off site and give full information on components such as windows and doors.

The information generated from drawings is not only a matter of describing requirements and translating them into a physical reality, but also a matter of communicating these requirements to different entities, making sure that their meaning is understood and that these requirements are fulfilled accordingly (Pietroforte, 1999).

The development of CAD and new digital media enabled big improvements in the way design information can be represented, presented and manipulated. They offer new ways of presenting design information visually, audibly, and recently even with tactile feedback, with increasing realistic results. Access to design information has become faster while interaction with representation has become almost commonplace.

3.7 BUILDABILITY

Building is a process of assembling components and the ability to assemble these components logically, accurately and quickly depends on understanding the interfaces between them. The larger the number of components, the more the number of interfaces to be managed and the more difficult it is to carry out the work which may result in delays and high cost (Ferguson, 1989).

3.7.1 What is Buildability?

The emergence of buildability as a research area is due to the long existing fragmentation of the construction industry and the demarcation between the design and construction processes (Moore, 1998; Ma et al., 2001). Buildability, known in the North American construction industry as constructability, can be considered as a major factor in measuring the success or failure of a project. Improving the buildability of a facility design has became a key concern for designers, builders and owners as improved construction operations can cut construction costs (Staub & Fischer, 1998). Therefore, it is an improvement area of interest to many researchers and practising engineers and architects.

Interest in buildability began in the early 1980s when a research programme was undertaken to identify major problems in the construction industry by the Construction Industry Research and Information Association (CIRIA) (Ma et al., 2001). In 1983, CIRIA published a report entitled "*Buildability: An Assessment*" which defined buildability as 'the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building'. This work highlighted the separation between design and production in the British industry, identified in earlier reports (e.g. Emmerson Report 1962) which advocated greater simplicity, more standardisation and better communication between designer and builder.

In the USA, the Construction Industry Institute (Jergeas & Put, 2001) defined constructability as "the optimum use of construction knowledge and experience in planning, engineering, procurement, and field operations to achieve the overall objectives". The work set out fundamentals of constructability outlined in a set of 17 principles that apply to conceptual planning, design, procurement, and field operation phases of a project.

In Australia, the Construction Industry Institute defined buildability as "integration of construction knowledge in the project delivery process and balancing the various project and environment constraints to achieve project goals and building performance at an optimal level" (CII Australia, 1996). The research report set twelve constructability principles that apply to feasibility, conceptual design, detailed design, construction, and post construction phases of a project. These principles form the basis of the constructability system.

Griffith, (1989) states that buildability is a shared responsibility between all those disciplines involved in building design and construction including architects, engineers, surveyors, building contractors and sub-contractors, and not the individual responsibility of the architect. Illingworth (2000) defines buildability as "design and detailing which recognise the problems of the assembly process in achieving the desired result safely and at least cost to the client", while Ferguson (1989) defines it as the ability to construct a building efficiently, economically and to an agreed quality level from its constituent materials, components and sub-assemblies.

Although the above definitions, given by various organisations and researchers, appear to be somewhat different from one another, the underlying concepts are very similar. All the above definitions focus on the issue that the benefits of buildability can solely be achieved by the integration of construction knowledge and experience into each phase of the project delivery process.

3.7.2 Buildability during Design Stage

One reason why buildability problems are not discovered during the design stage is that checks are usually performed using 2-D drawings. In addition, design details are sometimes very difficult and even impossible to construct, this is often a result of design teams not considering problems which the contractor has to face on-site (Gray, 1983). This causes a lot of difficulties to many professionals involved in the construction of a building. Designers, for example, have to invest additional time to provide immediate alternative solutions as soon as a problem arises on-site. Contractors absorb cost overruns; and above all, clients who, in addition to increased cost, must contend with delays (Navon et al., 2000).

Many researchers claim that good buildability can be achieved through standardisation and rationalisation. Moore (1996) states that good buildability could be achieved through two main approaches: simplification and standardisation. The differing nature of the two approaches does not mean them being mutually exclusive; the two can be used in conjunction with each other. Table 3-1 presents the main aspects of each approach.

A number of researchers have developed computerised systems for buildability improvement. These systems can be divided into three types (Navon et al., 2000);

- The first type uses a database of known buildability problems, or examples of good practice. This type includes a system developed for the US Army Corps of Engineers (CLL 1998) which contains experience accumulated from a large number of projects. This approach lists a number of potential problems that engineers should be aware of and suggests solutions to them. Although this system is useful, it ignores the fact that in many cases the lack of awareness itself results in buildability problems.

Table 3-1: Nature of Standardisation and simplification (Source: Moore, 1996)

Standardisation	Simplification
1. Generally seen as being applicable task level only	1. Applicable at project activity and task level
2. Minimises component variety	2. No deliberate minimising of component variety
3. Avoids complexity by adopting a position of minimum opportunity for its occurrence	3. Seeks to identify non-essential complexity
4. Preference for prefabricated, factory produced components	4. No explicit preference for prefabricated components
5. Maximises operative skills development in narrow areas of expertise	5. Considers the level of operative skill required over wide areas of expertise
6. Requires specific consideration as to how non-standard aesthetic requirements can be included	6. Places no aesthetic restrictions on the process of design
7. May force innovation in minimising component variations, but restricts creativity	7. Does not restrict innovation and seeks to encourage design creativity

- The second type integrates buildability knowledge within an automated design system, such as the system developed by Alshawi and Underwood (1996). The system developed deals with exterior cladding and lining taking into account the elements available, installation sequences, building codes, etc. The system can also recommend changes in building measurements to reduce the need for manual completions. The system generally offers concepts that prevent specific buildability problems but it does not diagnose a given design.

- The third type analyses an existing design from an execution viewpoint using a system that examines the design and informs the engineer of any buildability problems (Fisher, 1993). The problems that this system deals with are those related to the dimensions of the building elements that do not correspond to the standard form-work available. Another application that identifies clashes between services systems (electrical, air-conditioning ducts or water supply, etc.) using 3-D models was developed by Kuprenas et al. (1995). Navon et al. (2000) criticised this application, stating that it may mistakenly identify joints or junctions as a clash between two elements as the application uses separate entities for each element (e.g. electrical lines, ducts, water pipes, etc.).

3.7.3 Contractors Contribution to the Improvement of Buildability

Among buildability problems is the lack of co-ordination between the various disciplines (architectural, structural, service installations, etc.) and the low level of involvement of contractors at the design stage (Navon et al., 2000). There is increasing awareness that building contractors can significantly contribute to improved design buildability. Considerations of the problem of buildability within the construction industry has suggested that designers must become more aware of both the construction and cost implications of their design decisions. This may be achieved in practice if contractors are consulted early during the design process and encouraged to share their construction expertise when it may be most effective (Griffith, 1989).

3.7.4 Communication of Buildability Information

Buildability is mainly communicated through production drawings supplemented with specifications. The drawings provide static, as-built information, giving no details as to how the building is to be put together, the specifications are concerned with quality control defined in terms of amount and type of materials with reference to relevant codes of practice and regulations. If information of this type is too detailed it may become an obstacle to rational assembly (Ferguson, 1989).

Producing buildable design details is an important objective for buildability where communication of clear designs to other participants in the construction process of a project is crucial. Therefore, communication of information is regarded as an important factor for buildability, especially for people who use the information in the construction process, such as contractors and suppliers. An effective and efficient communication tool is essential to avoid misunderstanding of design details by others (Hassan, 1997). Good buildability may only be achieved on site if the design intentions are clearly and efficiently communicated to the building contractor (Griffith, 1989).

The principal means of communicating the designer's ideas, intentions and requirements to the site is by drawings, written instructions or mock-ups. These communication media are the source of understanding or misunderstanding of how the proposed building components are fitted together (Ferguson, 1989). If that link is weak then the production process will be time consuming and faulty construction could be the result (Adams, 1989). Therefore, the quality of a constructed facility can be improved by better communication among project participants such as designers and construction practitioners (Russell et al., 1999).

3.8 VISUALISATION

Visualisation is a way of representing data to improve their interpretation. It can also assist in understanding concepts and communicating them, "A picture is better than a thousand words". Computing power is increasing and becoming more and more affordable. CAD has already revolutionised design representation and in some instances, designs as well. Computer advances have enabled developments in visualisation making it a more effective tool, not only in the representation of design but also in academic research.

There are many definitions of visualisation; for example, Gallagher, (1995) stated that visualisation is the process of making complex states of behaviour comprehensible to the human eye while Rodriguez (1992) defines visualisation as the creative ability to form a mental images.

Visual thinking uses three kinds of visual imagery; the first one is the kind that we actually see; the second is the kind that we imagine (see) in our minds' eye, as our dreams; the third is the kind that we draw or model (to help others visualise our ideas).

Visualisation can take several forms. A simple line drawing can be regarded as sufficient means for some applications, whereas, rendered images may be needed for other applications. In design, visualisation is the overall imagining and visual-thinking process involved in conceiving, developing, modelling, simulating, testing, documenting, and marketing a device or a structure (Rodriguez, 1992). The visualisation of building designs developed gradually in thinking and technology from perspectives to interactive virtual reality models (Bertol, 1997).

Visualisation covers a wide spectrum of tools ranging from 3-D CAD models to VR (real time interactive worlds). Information visualisation has evolved to an established technique for the effective communication of information, especially with the uptake of the World Wide Web technology (Romero and Wiegand, 2001). These techniques can facilitate the process of interpreting data, representing the results for discussions, and feedback in design and construction meetings (Bouchlaghem, 2000).

3.8.1 Computer Generated Visualisation

Construction is shared and subdivided between different contractors and sub-contractors making exchanging design drawings and information in construction projects is a difficult process (Yoshihiko et al., 1999). Effective use of information technology in the form of computer based visualisation can help this process. Computer visualisation tools can facilitate the generation of images from complex multi-dimensional data sets (McCormick et al., 1987). In building design, computer visualisation can enable investigations to be conducted to identify buildability problems before construction commences on site (Li & Love, 1998).

Computer visualisation techniques cover a wide range of tools depending on the purpose of the application. The main types of computer generated visualisation techniques are (Earnshaw et. al., 1997):

1. Static graphical displays designed to be viewed on paper.

2. Three-dimensional representations using highly interactive software to be viewed and manipulated on high-resolution computer screens.

The rapid growth of visualisation applications in different fields including building design and construction is due to several tangible benefits reflected in following: (Brown et. al., 1995; Gallegher, 1995):

- It is possible to simulate something in real life;
- Computer simulation allows the observation of phenomena, which may be difficult or dangerous and sometimes impossible to reproduce physically;
- It allows us to evaluate automated design changes and analyse results;
- Visualisation can improve the efficiency of the design process.
- It makes possible the conversion of information that cannot be perceived by the human eye into forms suitable for the most highly developed human sense;
- Three-dimensional visualisation techniques allow the examination of complex phenomena that may not be possible to perform on traditional models.
- It provides us with much less physical testing at often substantial cost savings.

3.8.2 CAD Technology

Developments in Computer Aided Design resulted in 3-D modellers being readily available and affordable. Instead of being limited to 2-D drawings, designers are now able to create 3-D models of their designs, which can be used for generating various forms of presentations of which 2-D drawings (plans, elevations, sections, perspectives, etc.) are only part of. 3-D models are the basis for other visualisation techniques such as rendered images, which are used in stills (a single image), video animations (a fixed sequence of images), and real time simulations (Virtual Reality with direct interaction between model and observer).

The use of 3-D models as compared to sets of 2-D drawings, offer many advantages, (Leeuwen, 1999):

1. Relationships between information parts (e.g. plans and sections) are intrinsically part of the 3-D model.

2. Designing in three dimensions offers more insight in the geometry of a design and helps to maintain consistency in the design of details.

3. Consequences of modifications anywhere in the design become visible in a much more direct manner. As a result, errors during the preparation of the model and its interpretation can be significantly reduced.

There are several obstacles for the widespread use of 3-D modelling, such as the fact that their production is more difficult as well as more time and cost-consuming (Dorner & Grimm, 2001). The other problem is that, although offering more insight in the geometry of a design, 3-D models still do not allow semantics to be explicitly modelled (Leeuwen, 1999).

3.8.2.1 Early CAD use in Design

From the early 1970's when CAD systems were introduced, their use in design has been criticised for their inadequate support for the iterative nature of the process of building design, as opposed to the drafting of the final solution (Gero, 1997). The use of computers for conceptual design has been inhibited by the lack of an intuitive interface, both for 2D and 3D drawings. In construction industry, CAD is still used mainly as a drafting tool (Gero, 1997).

3.8.2.2 *Information from Manufacturers*

The Royal Institute of British Architects (RIBA) has encouraged the use of manufacturers' drawings of components in architectural design practice. They have assembled a library of CAD files from manufacturers in 2D and 3D drawings. This library, which is updated twice a year, is called RIBACAD. Those using it have the advantage of accurately dimensioned pre-drawn components that can be added directly to drawings and 3D CAD models. Work at the Building Research Establishment (Newnham, *et al.*, 1998) is now looking at using VR models (in VRML format) to develop a library of product information from manufacturers.

A lot of research has been conducted in the use of 3-D computer generated models in construction planning and scheduling. Retik et al (1990) used the 3-D representation of a building project to assist planners in monitoring of the construction work progress. Zhang et al (2000), Subramanian et al (2000) and Koo and Fischer (2000) linked 3-D models with construction activity schedules. A 4D CAD model for a project can then be automatically generated for any construction period and can be played forward or backward in time, displaying building construction at activity level and site space utilisation. It enables the planners to detect any delays to the original schedule, find inconsistencies in the scheduled activities, and assess the overall construction process. Staub and Fischer (1998) conducted a research project on the use of 4D CAD (3D plus time) in the assessment of constructability reasoning to expose constructability problems related to access, temporary support, availability of work space, and completion of prerequisite work.

Li and Love (1998) introduced a computer system that enables a user to construct a 3D model efficiently using object models stored in element libraries. The system allows the user to 'walk through' the 3D design and have a realistic appreciation of the product before it is built. They believe this can significantly reduce the amount of rework caused by clients' requests for last-minute design changes. Seebohm and Wallace (1998) considered a 3D Modelling system for assembling three-dimensional architectural details. The system can assemble 3-D models of construction details showing all of the construction components. It is written in Common LISP allowing the developers to take advantage of object-oriented technology. Unfortunately, the system development was abandoned due to technical problems.

Newton (1998) used 3-D models for simulating site visits to study the links and discrepancies between working drawings and the completed building. Finkelstein (1998) and Clayton et al (2002) used 3-D models to compare virtual construction methods to physical design-build projects, and linking these 3-D models with the fourth dimension of time (4D) to illustrate the construction process and sequence for education purposes.

Yabuki and Shitani (2001) developed a prototype design generation system, conformance-checking system, and a product model for steel connections using 3D modelling. The system aims to enable designers to check the proposed design and make modifications based on the consideration of cost and constructability. The proposed system was designed to deal only with steel structure connections. Morozumi et al (2002) studied the use of 2D and 3D models in design thinking during the conceptual design process. Watson & Anumba (1991) addressed the need for integrating 2D/3D CAD systems and developed a prototype that could form the basis for an integrated 2D/3D CAD system for structural design.

3.8.2.3 Future directions in CAD Applications

Object oriented packages for high end workstations, such as MultiGen, and Alias Wavefront show the probable future direction of CAD. AutoCAD from AutoDesk currently dominates the CAD market though the Bentley Systems CAD package Microstation, also has a sizeable share. Whilst AutoCAD users use Kinetix 3D Studio MAX and VIZ for more advanced rendering functions, Microstation has now integrated rendering functions into the base CAD product (Microstation, 1998). The Microstation CAD software also has some QuickTime VR functions.

The integration of fully-fledged VR functions into traditional CAD packages, or the smooth transfer of CAD data to VR would greatly facilitate the adoption of virtual reality by the construction industry. Unfortunately this is a goal for the more distant future as currently data transfer from CAD to VR is clumsy and incomplete as discussed in Chapter 6.

3.8.3 Virtual Reality

Virtual Reality (VR) is considered to date back to Sutherland's Sketchpad System (Whyte, 2000) which is regarded as the first attempt towards an intuitive interface through which man-machine interaction could take place (Bertol, 1997). Sutherland (1965) described the early concept of the head-mounted display (HMD) and immersive 3-D computer environments.

Brown et al. (1995) defined virtual reality as a computer system that creates real time experience of a virtual environment. Baker (1993) stated that VR refers to the ability to computer generate realistic three-dimensional worlds that the operator can explore and interact with through a natural interface such as the glove and helmet. Hearn and Baker (1994) defined VR as a system where users can step into a scene and interact with the environment. Another definition of VR by Bertol (1997) is "a computer generated world involving one or more human senses and generated in real time by the participant's action".

VR differs from other types of simulations in that:

1- In VR, navigation through world is achieved in real time.

2- VR environments allow the participant to perceive and create objects of perception by action at the same time.

3- The user is immersed in a three-dimensional environment (the sense of immersion).

The VR feature of allowing the designer to be immersed in the three-dimensional computer generated environment, makes it a very effective way of testing proposed building designs and the impact that they will have on the existing environment after their construction. Identifying mistakes and problems is easier through immersive evaluation than by looking at two-dimensional drawings or static three-dimensional (physical or computer-generated) models.

3.8.3.1 Types of Virtual Reality

Virtual reality systems can be divided into three main groups:

Immersive VR System: which attempts to present the viewer with the convincing illusion of being fully immersed in an artificial world (Issa, 1999) by replacing our view of the real world with computer-generated images that react to the position and orientation of the user's head. Immersive VR requires the use of simulators, data gloves, headsets and the like. These VR systems provide the user with a personal view of the virtual environment using a Head Mounted Display (HMD), which visually isolates him from the real world. The user can acquire a positive sense of being immersed in the virtual environment (VE), which is further enhanced when touch and sound are introduced.

The unique characteristics of immersive virtual reality can be summarized as follows:

- The virtual world is presented in full scale and relates properly to the human size;
- Realistic interactions with virtual objects via a data glove and similar devices allow for the manipulation, operation, and control of virtual worlds;
- Head referenced viewing provides a natural interface for look-around, walk-around, and fly-through operations;

- Stereoscopic viewing enhances the perception of depth and the sense of space; and

- The convincing illusion of being fully immersed in an artificial world can be enhanced by auditory, haptic and other non-visual technologies.

Non-Immersive VR Systems: An alternative form of VR, requiring cheaper equipment and providing less realistic feedback from the synthetic environment, is based on non-immersive techniques. Non-immersive VR also places a user in a simulated 3D environment that can be directly manipulated using a mouse or an equivalent pointing device.

A view into a VR world is displayed through the computer screen with 3D depth cues: perspective view, hidden-surface illumination, colour, texture, lighting, shading, etc. Animation and simulation of scenes are interactively controlled in response to direct manipulation through the keyboard and the pointing device. Devices are cognitively distant from user's concept of methods for affecting reality (e.g., mouse control motion is often used to cause locomotion in VR). With the non-immersive techniques the terminal becomes a window through which a person views a VR landscape. A non-immersive system, on the other hand, leaves the user visually aware of the real world but able to observe the virtual world through some display device such as graphics workstation. Desktop VR applications do not generally demand the highest graphics performance, meaning that the top of the range 'PC clones' may be used. To enhance interaction, devices such as 'Space Ball' may be used. The main advantage of the desktop VR is that its cost is lower than other forms of VR systems. However, desktop VR systems provide almost no sense of immersion in the virtual environment. For some applications desktop VR may be adequate.

The user views non-immersive virtual world through a wide spectrum of displays:

- ImmersaDesk/WorkBench Large table-top screen titled 45-degrees backwards;

- Large-screen projection (PowerWall);
- Conventional monitor; and
- All imagery is presented in stereo using stereo vision glasses.

The user controls in virtual world through a range of hand control devices:

- Wand (3-D mouse);
- SpaceBall (6-DOF force stick);
- Mouse;
- Trackball;

Mixed Reality Mixed Reality refers to models which combine a real environment and Virtual Reality. In the mixed reality continuum (Drascic & Milgram, 1996), Augmented Reality (AR) displays are those in which the image is of a primarily real environment, which is enhanced, or augmented, with computer-generated imagery. Using a see-through head-mounted display, for example, it is possible to make ghost-like images of anything we desire appear before the viewer in a fairly-well specified location in space (Sowizral, 1994). These images can display information, or can serve as interactive tools for measuring or controlling the environment.

In contrast, Augmented Virtuality (AV) displays are those in which a virtual environment is enhanced, or augmented, through some addition of real world images or sensations. These additions could take the form of directly viewed (DV) objects, where the users might see their own bodies instead of computer-generated simulations (see Figure 3-4). Augmented Virtuality could also combine VR with stereoscopic video (SV) images, where for example the view out of a virtual window might be of the real world at a distant location. Augmented Virtual Tools are an example of AV that were developed in order to solve a major limitation of VR, which is the absence of the sense of touch. In this system, real objects are fitted with special sensors and are used as the physical components of input devices for a VR system. The user "sees" virtual representations of these objects through the VR headset, which can have arbitrarily complex characteristics and functionality (Sowizral,1994). The illusion that the real object and the virtual one are the same thing is maintained as long as the displayed shape matches that of the real object, and its perceived size and location are approximately correct (Drascic & Milgram, 1996).

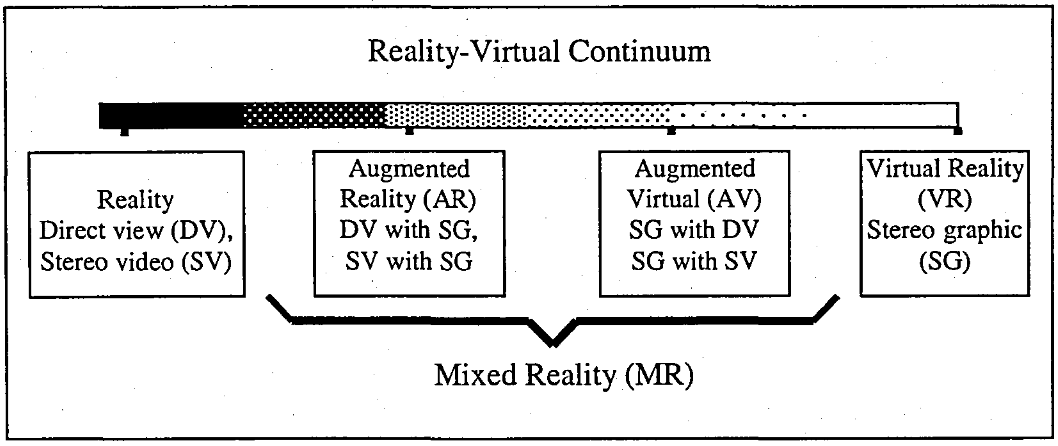


Figure 3-4: Simplified representation of the Reality-Virtuality Continuum, showing how real and virtual worlds can be combined in various proportions, according to the demands of different tasks (Source: Drascic & Milgram, 1996)

When the site is not accessible it is possible for generated models to be overlaid on video footage gained using telepresencing. A mobile, real-time, 3D hybrid virtual reality and telepresencing (VR/TP) systems are developed by Stone et al (1999) and O'Connor and Retik (1998). These systems will allow remote surveillance of the construction site, and integration of real world images of the site with virtual reality representations, derived from planning modules, for progress monitoring. The advantage of this merging of real and synthetic images is that it eliminates the need to rebuild the existent world. Only the new development itself, or textual data relating to it, need be modelled in the virtual world. However the use of real images limits the views that can be taken of the model. The real images need to be taken, either directly with the eye, or with a robotic head that can be controlled. It is not possible to gain the kind of exocentric viewpoint that can be seen in a purely virtual world. Tracking the viewpoint is extremely complex, the Columbia University project (Feiner, 1996) is military funded and three extra terrestrial satellites are used in order to accurately determine the users location.

3.8.3.2 VR and the Internet

The Internet has grown at a phenomenal rate during the last decade and has moved from a text-based service (FTP) to one that can display graphics and text (HTML). This continued expansion of the Internet the continued increase in data transfer speeds alongside the availability of affordable and powerful computer hardware, has helped the growth of Internet sites containing 3D models that can be viewed in real time (VR). This format is fast becoming one of the most popular ways of delivering information over the Internet. At the moment there's a wide range of applications for this technology:

- Real time 3D environments (VRML);
- Retail (on-line shopping);
- Leisure (games); and
- Heritage (virtual museums and re-created historical sites).

VRML is an acronym for "Virtual Reality Modelling Language". It is a file format for describing interactive 3D objects and worlds to be experienced on the world wide web (similar to how HTML is used to view text). The viewing of VRML plug-in for web browsers is usually done on a graphics monitor under mouse-control and, therefore, not fully immersive. However, the syntax and data structure of VRML provide an excellent tool for the modelling of three-dimensional worlds that are functional and interactive and that can, ultimately, be transferred into fully immersive viewing system. There are 2 Versions of VRML at the moment VRML 1.0 and VRML 2.0. Version 1.0 can be used to create and view static 3 dimensional worlds. Version 2.0 is much more powerful with interactive features, which include animation, sound effects, and user interaction.

3.8.3.3 The use of Visualisation and VR in design and construction

Visualisation has always played an important role in the process of building design and construction to represent ideas and concepts. This can take the form of scaled down physical objects or computer generated CAD models. Latest advances in computer technology and multimedia led to big developments in the use of computer-based visualisation covering the whole design and construction lifecycle.

Virtual reality (VR) is one of the hottest research and development areas in the computer industry today. Its potential applications range from medical imaging and interior design to intercontinental videoconferencing and the exploration of future worlds. There are a number of ways in which virtual reality technology can be employed; its underlying premise, however, is to create more intuitive ways for humans and computers to work together.

It is assumed that VR will reshape the interface between people and information technology by offering new ways for the communication of information, the visualisation of process, and the creative expression of ideas. Note that a virtual environment can represent any three-dimensional world that is either real or abstract. This include real systems like buildings, landscapes, underwater shipwrecks, spacecrafts, archaeological excavation sites, solar systems, and so on. These virtual worlds can be animated, interactive, shared, and can expose behaviour and functionality. This section looks at previous research projects that use VR in AEC.

Work into the use of Virtual Reality for spatial modelling at the conceptual design stage has been addressed by both general research projects, such as Stanford's

DesignSpace (Chapin, *et al.*, 1994) which focused on simple surface and solid geometric shapes, and more specifically architectural projects. Examples of architectural projects are Weimar's VoxDesign software (Dirk & Regenbrecht, 1995), Georgia Tech's immersive application Conceptual Design Space (CDS)(Eastmann, 1997), and the COVIRDS (Conceptual Virtual Design System) at the University of Wisconsin-Madison (Dani & Gahd 1996). Tizani and Ruikar (2000), at Nottingham University, developed a system aimed at supporting integrated design process through working with the virtual building. The system is developed in C++ and OpenGL using object-oriented, knowledge-based systems and virtual reality techniques. It attempts to bring together integrated analysis and design, connection modelling design, cost modelling and appraisal, knowledge-based advice and interactive virtual reality. Soemardi (2000) attempted to provide a system that would help users (design engineers) to exercise constructability analysis of constructing and/or installation of pre-cast concrete elements. This research aims at exploring the utilisation of virtual reality technology to help both the designers and the practitioners in the construction industry to have better control in the design and erection processes of precast concrete elements.

The software package Sculptor (Kurmann, 1997) developed at the ETH, Zurich, is a particularly good example of a volumetric modelling tool, designed as part of one such architectural project, as this package introduces the concept of the "space element". A "space element" is an element that consists of no material and carves out a space when it intersects with a solid element. Instead of using solid volumes and Boolean operations such as subtraction, union, or difference, the Sculptor package introduces two types of volume, positive (solid) or negative (space). The result is a more intuitive approach to the use of the computer as an architectural design tool at the conceptual design phase. Feeding the output of such a tool into the detailed design stage is an important issue that is still unresolved.

3.8.3.4 *Simulation*

Simulation of the Construction Process

Early work on the simulation of the design and construction processes was done by Op den Bosch and Baker (1995) at Georgia University. The Interactive Construction Visualiser (IVC) was created in 1991 as part of Op den Bosch's Ph.D. project. The virtual environment produced, written in the object oriented language C++, provides the user with a choice of virtual construction equipment that can perform the tasks needed to assemble buildings. The project has laid a heavy emphasis on the production of virtual construction equipment, which the users can then interact with to assemble virtual buildings. In this way attention is focussed on engineering issues relating to the building construction, as opposed to technical computing issues relating to the building model's creation.

At Strathclyde the construction sequence has been simulated allowing the user to see progress at various stages of completion (Retik 1996). It is hard to see a current commercial application of this research, as the approach used has been to develop these simulations in isolation, without the import of CAD or other available development data. The rationale behind this approach is that much of the simulation data required simply doesn't exist in other geometric formats. An item in a CAD database, such as a concrete beam, is simply a geometrical description and doesn't have associated information about it's construction process, such as the placing of the steel rods, the pouring of the concrete etc. However the parts used by Retik in the VR environment are such small elements of a complete building project, (i.e. individual walls, columns, slabs, flooring, plastering stucco etc) that it would take a long time to put together any one simulation of any specific building project. A lot of the work involved in building the VR model is repeated from work that has been done previously in other packages such as CAD and Gantt charts. If future computer aided design is based in virtual environments then this approach will have more use from an industrial perspective, until then its lack of connection with other sources of information is a serious shortcoming.

The OSCON project at Salford (Aouad et al, 1997) also has the capability of simulating the construction process. This project has the advantage of being integrated with other project applications including CAD and Process Management through a common central project model. This means that data entered in CAD is available in VR. Indeed Aouad argues that VR should be used as an interface to the integrated project database, which can be remotely interrogated across the World Wide Web. Some data is still unique to the VR environment but repeated data doesn't require re-entering.

At Stanford the CAD model is taken as being the basis for a common language between all parties involved in the design and construction of buildings. Time is added to the 3D model creating a visual simulation of the construction process, or 4D CAD (Fischer, 1997). In the first quarter of 1995-1996 a prototype 4D-CAD tool was developed, which operates in the AutoCAD environment and links to D++ symbolic modelling environment. With 4D-CAD, design and construction planning alternatives can be assessed within the context of space and time. Simultaneous modelling of temporal and spatial aspects of case study can optimise and justify the conscious decisions that jeopardise or hinder the completion of many construction projects (Fischer & Aalami, 1996). However this project is not integrated with other project applications, and as such is not as ambitious as the OSCON project (Aouad et al, 1997).

Simulation of Human Activity in Buildings

After the King's Cross disaster, work on the use of VR to simulate egress of buildings in case of fire was done jointly by the BRE and Colt VR Limited for the London Underground (Griffin, 1995). Colt VR Limited had been involved in early work on the use of VR for simulation of real life case studies, and virtual fire drills have also been simulated at Eindhoven (Smeltzer and Roelen, 1995).

Simulation of Environmental Factors

Early CAD systems which included simulation of building behaviours include the Gable CAD package developed at the University of Sheffield in the 1980's. The results of calculations about day lighting etc were however found to be hugely inaccurate when compared to real buildings, because of the complexity of and difficulty of modelling real world systems (verbal communication with Gable user, 1998).

Pangea is another intelligent design tool, developed as a research project (Penn et al, 1996), and aimed at the three dimensional sketch design stage of building and architectural design. It has the ability to model non-geometric information relating to building designs. Three dimensional and abstract objects in the modelled world have an internal state, defined by attributes, constraints, defined by rule sets, and behaviour, for example to simulate the effects of lighting, heat, air-flow, pedestrian movement and other processes within a built world.

Virtual soundproof simulation (Shinomiya, 1994) has been developed by the Japanese company Matsushita Electric Works Ltd., which supplies housing materials. They have been actively researching the use of virtual reality simulation of lighting, ventilation and acoustics. In their work on soundproof simulation, virtual acoustics are used to analyse the acoustic performance of the dwelling whilst walking through the virtual house.

3.8.4 Product Modelling and Visualisation

A building product model is potentially a richer representation than any set of drawings which can be implemented in multiple ways, such as an ASCII file or a database. The data in the model will be created, manipulated, evaluated, reviewed, and presented using computer applications, some of which are extensions of the present computer-based design and engineering tools (Eastman, 1999).

The mid-1970's marked the beginning of efforts to develop integrated systems, based on a single building model supporting a suite of applications (Mourshed et al,2001). The distinctive early works were OXSYS CAD, SSHA-Edinburgh in the UK and ARCH-Model, BDS and GLIDE in the US (Eastman, 1999). The goal of product modelling and data exchange is to make the exchange and sharing of information among multiple applications easy and an everyday occurrence (Augenbroe & Eastman, 1998). After twenty years of product modelling development - first in the area of building modelling and in the last ten years primarily centred around the ISO-STEP (STandard for the Exchange of Product model data) efforts, and more recently augmented by the IAI (International alliance on Interoperability). The schema of the former is called STEP while the latter is called IFC (Industrial Foundation Classes).

Current initiatives on exchange of product data in the broad sense are primarily focused on graphical data – 3-D representations for visualisation, CAD files distributed in generally accepted formats, etc. Sample portals are GDL Technology /GDL Central, which is based on the *Geometric Description Language* (GDL) from Graphisoft, and CADABRE, which is based on AutoDesk technology. GDL Technology is a technology and GDL Central is a service provider for component manufacturers in the building industry (Jorgensen, 2002). Because GDL objects can be formulated with parameters, it is possible to model product families in one object. This is especially beneficial regarding product model maintenance. GDL Technology claims that more than 100 manufacturers of building components already have produced and published more than 30.000 GDL models representing over 300000 end products (Jorgensen, 2002).

Several efforts to utilise a database approach to VR models creation using a centralised database to control characteristics of components and both CAD and VR were used as graphical interfaces to the database. Open Systems for Construction (OSCON), for example, is a research project conducted at University of Salford used case studies from real-life construction projects to demonstrate usefulness of database approach (Aouad, et al., 1997). In this project, a core module that includes process management, planning, CAD, estimating and VR was used. Other attempts were conducted by Alshawi, 1995; Eastman, et al., 1997 and Cooper, et al, 1992.

3.8.5 Computer Supported Collaboration Working

The Internet has greatly facilitated Computer Supported Collaborative Work (CSCW). Several universities, including MIT, Sydney, Cornell, National University of Singapore (NUS), University of British Columbia (UBC), and ETH in Zurich are participating in a studio project called the Virtual Design Studio, which is comprised of designers collaborating and observing each others design processes via electronic communication (Bertol, 1997).

Woo et al (2001) conducted a study on the use of VRML as communication tool in a multi-user workspace collaboration system. The aim of the system was to assist designers in reviewing design while solving various specialised problems. The system allows various actors who are geographically distributed to communicate remotely and collaborate. VIRTUS is a collaborative multi-user Platform developed at Karlsruhe University (Germany) that allows multiple geographically distributed users to manipulate shared VRML scenes (Saar, 1999). ToolSpace is another system developed at Emory University (USA) that supports collaboration (Goddard & Sunderam, 1999).

Multi-user virtual environments can be a medium for the remote collaboration of designers, and the discussion of design proposals by the general public. A virtual model of the new railway junction of Porta Susa, and the surrounding urban context was made at the Politecnico di Torino in Italy in collaboration with the municipal authorities (Caneparo, 1997). The model is part of a large collection of on-line information, including documents, drawings, drafts, blueprints, pages of reports, and technical specifications, letters, manuals etc. relating to the project. It was opened to the public online on the Internet, so that they could experience and discuss the new urban proposal. The multi-user module used integrated a chat program in which users were embodied as avatars in the world, and could exchange brief written messages.

Over 200 participants from all over the world arrived in the model, but it was difficult for the researchers to focus the discussion and the anti-social behaviour of participants led to the termination of the open discussion. Earlier work on CSCW (Benford et al, 1995), using the DIVE and MASSIVE VR systems, has more extensively investigated the issues of human interaction in virtual environments. The live experiments that formed part of this work have also produced antisocial, mischievous and unpredictable behaviour.

Whilst in the above projects all the users had the same interface with the world, it is possible to give users different degrees of functionality and different abilities to alter the world from within. Heterogeneous perspectives are investigated in the CALVIN (Collaborative Architectural Layout Via Immersive Navigation) project undertaken at the University of Illinois (Leigh & Johnson, 1996). Two different perspectives are introduced; the "mortal" view which is egocentric and the "deity" view which is exo-centric. Mortals and deities may be assumed the roles of apprentices and teachers or clients and demonstrators. Leigh and Jonson write, "Although the single ego-centric perspective is useful in the evaluation of a pre-designed space, it may not be the most appropriate perspective for the actual design of that space". This opinion is supported by the experimental data discussed in relation to issues of abstraction and cognitive maps.

In the CALVIN project the different users, mortals and deities, do not have a homogeneous interface to the virtual environment, mortals are more capable of performing fine manipulations and deities are more capable of performing gross manipulations. The use of different viewpoints and roles in the CALVIN project could be usefully extended to characterise the viewpoints of a range of building professionals on a construction project, each with their own interfaces to the world which could filter world information and allow different interaction with the world.

3.8.6 Computer mediated Communication

Paper-based communication of project information is no longer considered adequate to cope with the high level of functionality (in terms of speed, accuracy, usability, ease of modifications, enhanced visualisation, improved co-ordination, etc.) required in a collaborative working environment (Anumba et al., 2000). In addition, much of the information that is conveyed by drawings is implicit, and relies heavily on interpretation (Kalay, 2001). The use of an efficient communication system, therefore, will improve the communication and collaboration in solving design and construction problems between design and construction teams (Alshawi and Underwood, 1999).

A computer supported communication for a design that can be used in construction industry may include (Cicognani and Maher, 1997; Anumba and Duke 1997):

- *Electronic mail: E*-mail is regarded as the fastest, cheapest communication medium between people who have access to a computer network. Messages can be sent from one person to another who has a unique address that called an e-mail address. E-mail is regarded as the universal network communication media for computer mediated communication for collaboration. This is mainly due to the low cost, high level of connectivity, platform computability, and transcendence of time and space (Sudweeks and Allbritton, 1996). In the networked organisation, the informality and interactive features of e-mail encourage employees to cross social and organisational boundaries to share opinions and ideas. However, text-based communication is commonly compared unfavourably with face-to-face interpersonal communication because participants cannot hear intonation that signals a joke, or see puzzled expressions that convey confusion (Sudweeks and Rafaeli, 1996).

- *Videoconferencing:* This type of computer communication allows a group of people to see a video of the other participant while taking any type of action such as talking, drawing, or typing on a shared window. It provides a good means of communication between two or more participants who may be far away from each other. The widespread use of videoconferencing is hindered by the cost of setting up dedicated systems in special-purpose viewing rooms (Pietroforte, 1997).

The Internet: The Internet is a network of computers, which are geographically distributed all over the world. The information on it can be exchanged and communicated. Any person in the world can gain access to information that has been made available on the web except where information has been restricted and where a password is required. World Wide Web pages that record design information can be effective tools for design collaboration.

3.9 SUMMARY

In this chapter the use of computer visualisation as a communication tool in collaboration between different disciplines of construction, buildability and the various research efforts towards its implementation, have been discussed. Designers are able to evaluate and assess their design alternatives by building 3-D computer generated visualisations where amendments are easy, cheap, and less time consuming. Computer mediated communication is increasingly gaining importance in research studies on a range of issues relating to support for geographically remote collaboration. Collaboration could be a fundamental part of effective decision-making and problem solving, especially in complex design and the construction of projects. It may be regarded as an appropriate method for producing better products faster and for a low cost. The construction industry faces high competition and many large projects have been carried out by different companies in which their offices are geographically distributed. Any tools that have the potential to support fast information exchange should be introduced sooner. However, although there is a need for adopting computer visualisation as a communicate tool for exchange of design information related to buildability problems at the construction stage of a facility, current research efforts do not address the issue of the industry needs that computer visualisation can fulfil. The development of a prototype system, for the use of computer visualisation to communicate design information, is, therefore, essential for improving communication/collaboration in the construction industry. However, this must be preceded by an investigation of current use of computer visualisation and the buildability problems that occur during the construction stage of a building. Therefore, an industry survey has been conducted to achieve this aim. This is the subject of the next chapter.

Chapter Four
Industry Perspectives on Role of Visualisation in Buildability

CHAPTER FOUR

4 INDUSTRY PERSPECTIVES ON ROLE OF VISUALISATION IN BUILDABILITY

4.1 INTRODUCTION

One of the main objectives of this research is to study the industry perspective on the role of visualisation in communicating design information between design and construction teams during the construction stage of a building project. Chapter Two discussed various research methods for data collection; outlined the specific strategy and methodology for data collection for this research study. As in Chapter Two, the specific research methodologies used were a questionnaire survey and case study interviews.

This chapter presents the results of an investigation into the use of visualisation tools (traditional and computer based) for communicating buildability information during the construction stage of a project. It also investigates the collaboration between designers and contractors to solve design problems. It is split into two main sections, the first section presents details of a questionnaire survey of contractors and consultants, the second section presents semi-structured interviews conducted with eight contracting and consulting organisations (four each).

4.2 INDUSTRY POSTAL SURVEY

The postal questionnaire technique is suitable for gathering information from a large sample who may be geographically dispersed. This technique was adopted for this research for the following reasons:

- To enable a large sample of construction industry professionals, to be included in the survey;

- The population on which the survey is focused is geographically scattered in all regions in the UK;

- To receive the responses within a short period of time; and

- To limit the cost of data gathering.

4.2.1 Objectives of the Postal Survey

As described in Chapter Two, the main aim of the survey is to establish a general industry wide perspective on the role of visualisation in buildability. The research considered the use of these technologies within the organisation and when communicating with other participants in the design and construction of buildings. Other objectives included were to:

- investigate computer based communication infrastructure;

- investigate buildability problems that might arise during construction;

- investigate the level of collaboration between design and construction teams especially during the construction stage;

- address the requirements of the communication and collaboration system needed; and

- assist in the development of the proposed visualisation system.

4.2.2 Questionnaire Design

To achieve the aims of the survey two questionnaires were prepared. An important aspect of conducting a questionnaire survey is to ensure the largest possible return to enable meaningful analysis. Therefore efforts were made to ensure that the questionnaires were not too elaborate for the respondents. The questionnaires included 16 questions and were divided into 5 sections:

- general information about the organisation;
- visualisation and communication tools available;
- buildability areas with potential problems during construction (based on Illingworth (2000) and Ferguson (1990));
- collaboration between site team and design team in solving design problems; and
- assessment of visualisation and communication tools and methods.

The first questionnaire was sent to contractors and the second was sent to consultants. The questions were generally of the closed type but with sufficient flexibility so that the respondents could include their own views. There are two benefits of closed questions: first, it is easier for the respondent to answer, and second it is a way of getting rid of unrelated answers (see Appendix B). All respondents were given the opportunity to reply anonymously, however most gave their addresses to obtain copies of the results.

4.2.3 Pilot Survey

It was important to carry out a pilot survey at the outset to check the appropriateness and clarity of the questions and to capture the recipients' possible reactions to the questionnaire (Moore, 1983; Lang & Heiss, 1984). Questionnaires need improvement and adaptation until they become mature. Therefore, every aspect of a questionnaire should be tried and tested to ensure that it works efficiently leading to the maximum amount of relevant information being gained.

In the current study, the questionnaires were piloted in two stages. Firstly copies of the questionnaire were sent to ten contractors and consultants: six completed questionnaires were returned, four of them contained only comments on the questionnaire design and content, these comments were taken into consideration in the design of the final questionnaire. Secondly, 10 copies of the two survey questionnaires were distributed to research staff within the department with experience in designing survey questionnaires. Their comments were also taken into consideration and helped considerably in the preparation.

Some of the actions taken based on the pilot survey stages were:

- The length of the questionnaires was shortened from six pages to four pages;
- The title was changed to make it more appropriate so that the respondents were not misled; and
- Some questions were rewritten for clarity.

4.2.4 Survey Sample

Two methods of sampling are cited in the literature, parametric and non-parametric sampling. Parametric sampling is where the probability of inclusion of any candidate in a sample can be specified and include simple random sampling; systematic sampling; stratified random sampling; cluster sampling; and multi-stage sampling (Sekaran 1992). On the other hand, if it is not possible to specify the probability of including a firm or person in a sample, the sampling falls under the non-parametric type which includes: quota sampling; dimensional sampling; convenience sampling; purposive sampling; and snowball sampling.

In this research, the sampling frame was confined to designers and contractors in the domain of construction firms. Construction contractors and consultants (designers) considered by recent studies to be the most needy with respect to the business process improvements (Egan 1998; McGeorge and Palmer 1997; Volpe 1991). Therefore, medium and large construction contractors and consultants became the primary candidates for this industry survey.

Table 4-1 Statistics of the contractors' survey questionnaires

Number of questionnaires sent	50
Number of replies received	28
Number of usable/useful replies	18
Percentage of total replies	56%
Percentage of usable/ useful replies	36%

The target groups included 100 contractors and consultants who were involved in the construction of office buildings. A total of 50-survey questionnaires were sent to contractors in March 2000. They were selected at random from the top 100 UK contractors based on turnover (New Civil Engineer 1999) and operation (building construction). The number of questionnaire replies mailed back by respondents was 28 (see Table 4-1). Of these 18 replies were usable, representing a response rate of 36% which is good considering the average of 20-30% response rate in postal questionnaire surveys in the construction industry (Easterbt-Smith et al, 1991; Akintoye, 2000).

The second set of questionnaires was sent to a total of 50 consultants in March 2000, randomly selected from the top 100 consultants' in the UK (New Civil Engineer 1999). The total number of replies was 16 (see Table 4.2). Of these 11 were usable, representing a response rate of 22%. The overall response rate was 29% for both contractors and consultants (see Table 4.3). The reasons for uncompleted questionnaires can be due to three main reasons:

- Pressure of work where respondents had deadlines to meet;
- Volume of questionnaires that the organisations receive; and

- The policy of the respondents' organisation is not to reply to any survey or take part in any research except that they sponsor.

Table 4-2 Statistics of the consultants' survey questionnaires

Number of questionnaires sent	50
Number of replies received	16
Number of positive replies	11
Percentage of total replies	32%
Percentage of positive replies	22%

Table 4-3 Statistics of the survey questionnaire

Total number of questionnaires sent	100
Total number of replies received	44
Total number of positive replies	29
Percentage of total replies	44%
Percentage of overall positive replies	29%

4.2.5 Results

The following sections present the results of the postal survey questionnaire. Firstly, general information about the organisations' size and their experience in the field of building construction was discussed. The results were divided into two main sections: consultants' perspective and contractors' perspective in order to make it easy for comparison to be made.

4.2.6 General Information

Table 4-4 shows that the vast majority 91% of the respondents had been involved in their field for more than 10 years. Table 4-5 shows the sizes of organisations surveyed according to the number of employees; 49% of these employ more than 100 staff. From this distribution of responding firms it can be deduced that this survey covers the spectrum from small, through medium, to large size construction practices and contractors.

Table 4-4 Years organisations have been involved in construction activities

Experience	Per cent
Less than 10	0
10-19 years	45%
20-29 years	9%
30-39 years	18%
40-49 years	0%
50-59 years	9%
Over 60 years	9%
Not indicated	9%

Table 4-5 Size of the surveyed organisation

Size of the organisation	Per cent
1-10 Employees	0%
11-24 Employees	9%
25-49 Employees	18%
50-99 Employees	18%
100-249 Employees	27%
250-499 Employees	9%
500-999 Employees	9%
Over 1000 Employees	9%
Not indicated	0%

4.2.7 Contractors' Views/ Perspective

Visualisation tools: 3-D models and rendered images are the most common types of visualisation tools used (twenty two percent of contractors use them) (see Figure 4-1). VRML is used by only 6% of respondents while animation and other virtual reality software are not used at all. 50% of contractors make no use of visualisation tools.

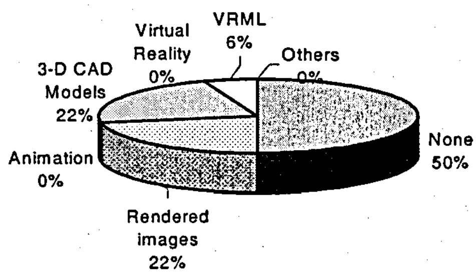


Figure 4-1 Visualisation tools used by contractor respondents

Computer communication: Table 4-6 shows the use of computer-based communication by contractors. It shows that e-mail is widely used by the respondents to communicate with their head office, designers, subcontractors, and other supply chain members. Electronic data transfer is the second most widely used communication medium. It is used 'Sometimes' to 'Frequently' by 66% of the respondents for communication with organisation head office. Internet and Intranet are used 'Sometimes' to 'Frequently' by 61% of the respondents. Other communication media (such as VR and video conferencing) are rarely used by respondents.

Table 4-6 Communication media used by contractor' respondents

Communication medium	The Organization Head Office			Design Offices			Subcontractor Offices			Supply Chain		
	1*	2*	3*	1*	2*	3*	1*	2*	3*	1*	2*	3*
E-mail	0%	17%	72%	11%	22%	44%	22%	28%	11%	28%	22%	28%
Video Conferencing	22%	0%	11%	6%	6%	6%	0%	0%	0%	0%	0%	0%
Electronic Data transfer	17%	22%	44%	6%	22%	28%	11%	6%	11%	6%	6%	22%
Virtual Reality	17%	0%	11%	6%	0%	11%	0%	0%	0%	0%	0%	0%
Internet/ Intranet	6%	17%	44%	0%	17%	22%	0%	28%	0%	11%	6%	11%

(1 Rarely 2 Sometimes 3 Frequently)*

Buildability problems: Difficulties with interfaces between components of service installations is the most common problem, and is experienced 'Sometimes' to 'Frequently' by most respondents (see Figure 4-2). This includes 83% for electrical

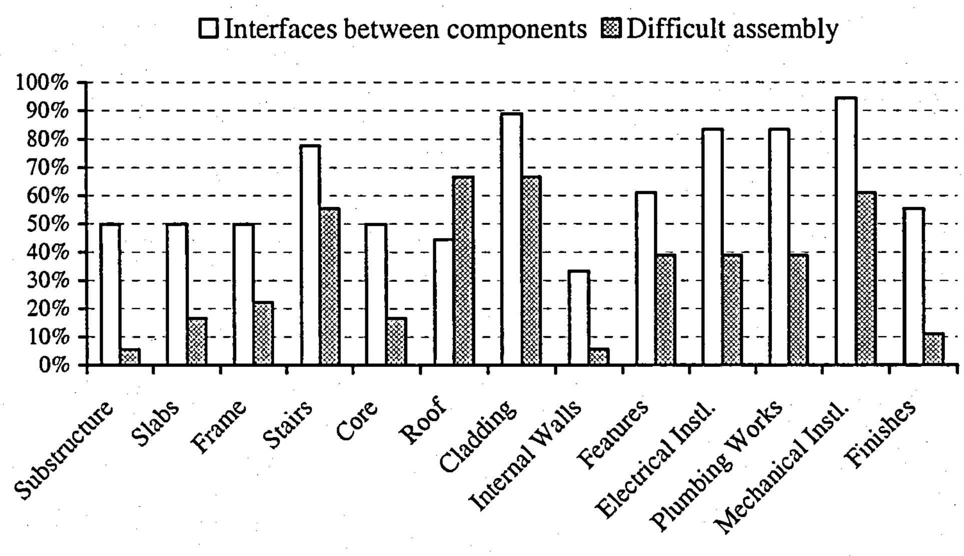


Figure 4-2 Buildability problems (contractor respondents view)

installations, 64% for plumbing works, and 94% for mechanical installations. The other main buildability area is cladding with 89% of respondents having 'Sometimes' to 'Frequently' experienced problems in this area. Stairs are regarded by 78% of respondents as a buildability problem area, 'Sometimes' to 'Frequently' causing difficulties in interfaces between components.

Roof and cladding are the buildability areas, which caused the greatest assembly problems as experienced by 67% of respondents. Assembling stairs is regarded as a problem area that have been experienced by 57% of the respondents. Sixty-one percent of the respondents 'Sometimes' to 'Frequently' experienced difficulties in assembling mechanical installations. Other buildability areas of less significance include the substructure, internal walls and finishes.

Generally, the most common problem is interfaces between components. Between 33% and 94% of the respondents have 'Sometimes' to 'Frequently' experienced this problem in one of the buildability areas.

Reasons for buildability problems: respondents were asked about the main causes of buildability problems they have experienced (see Figure 4-3). Over seventy percent of the respondents believed that conflicting design information is the most common cause of service installation problems. The main causes of cladding, stairs and roof buildability problems are identified as poor design detailing and conflicting design information.

Clarification of buildability information: clarification of information for buildability problems is mainly carried out using 2-D drawings, written statements and face-to-face meetings (see Table 4-7). Physical models, 3-D models and rendered images are infrequently used by respondents. The other methods such as 4-D CAD, video animation, VR and VRML, are not used at all.

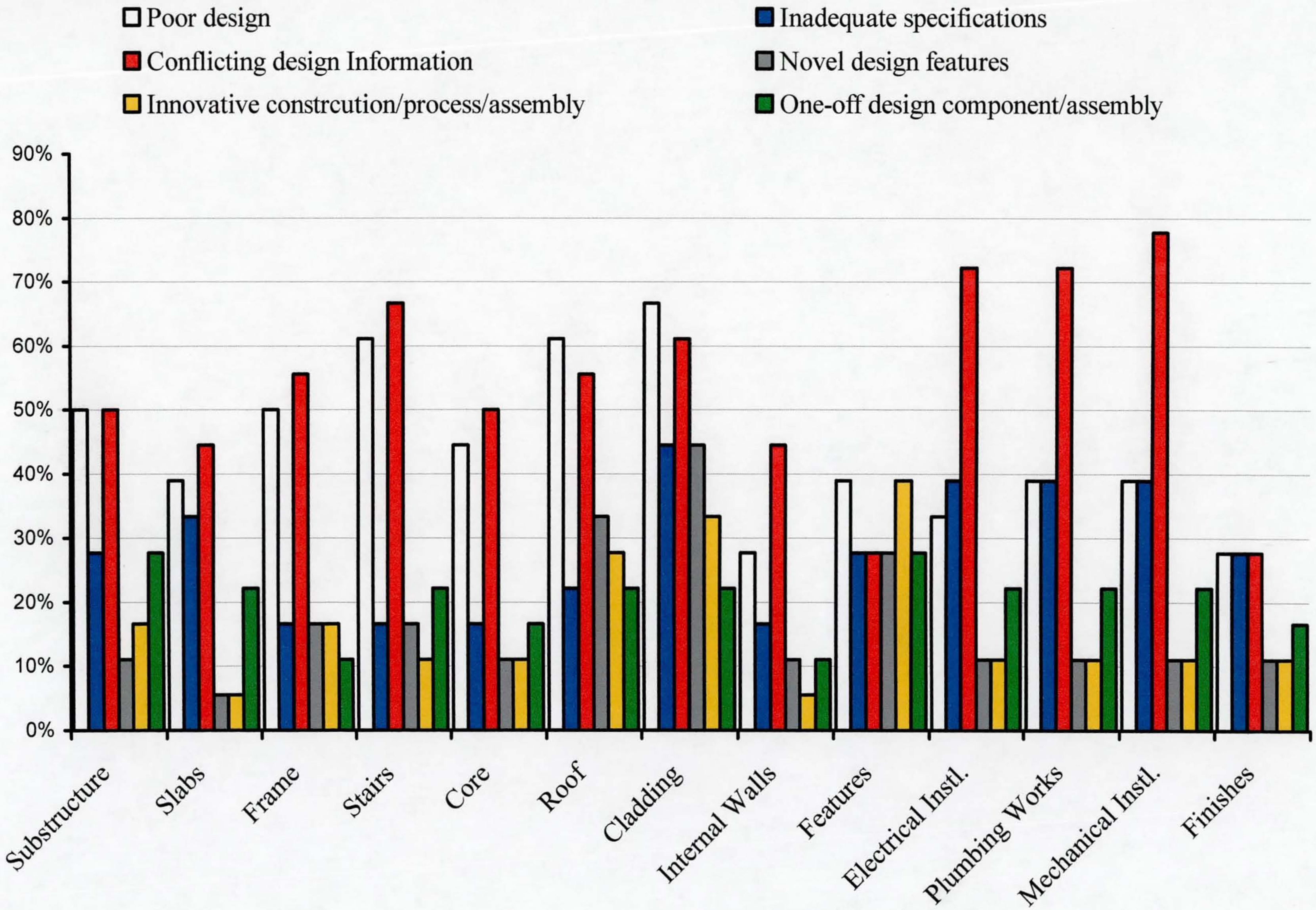


Figure 4-3 Causes of buildability problems (contractor respondents' view)

Table 4-7 Methods used by contractor' respondents to clarify buildability problems

	Written Statements	2-D Drawings	Physical models	Face to face meetings	3-D Models	Rendered Images	Video Animation	4-D CAD	VR	VRML	Present-ation on the Internet
Substructure	72%	78%	6%	72%	6%	6%	0%	0%	0%	0%	11%
Slabs	78%	61%	6%	67%	6%	6%	0%	0%	0%	0%	6%
Frame	78%	78%	17%	78%	17%	6%	0%	0%	0%	0%	6%
Stairs	72%	83%	6%	67%	17%	6%	0%	0%	0%	0%	6%
Core	78%	83%	6%	72%	6%	6%	0%	0%	0%	0%	6%
Roof	72%	89%	17%	72%	22%	6%	0%	0%	0%	0%	6%
Cladding	78%	72%	17%	72%	17%	6%	0%	0%	0%	0%	6%
Internal Walls	61%	78%	6%	72%	11%	6%	0%	0%	0%	0%	11%
Features	78%	67%	6%	72%	17%	11%	0%	0%	0%	0%	6%
Electrical Instl.	72%	83%	6%	72%	11%	6%	0%	0%	0%	0%	11%
Plumbing Works	72%	83%	6%	78%	11%	6%	0%	0%	0%	0%	11%
Mechanical Instl.	67%	83%	6%	78%	17%	6%	0%	0%	0%	0%	6%
Finishes	72%	72%	11%	72%	6%	11%	0%	0%	0%	0%	6%

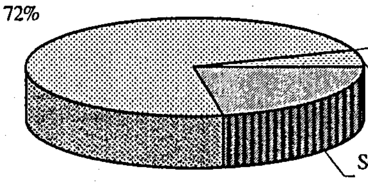


Figure 4-4 Recommending changes to design details during construction stage (contractor respondents)

Recommending changes to design details: Sometimes there is a need to make or recommend changes to design details on site. Seventy-two percent of contractors frequently experience (see Figure 4-4) a need to do so.

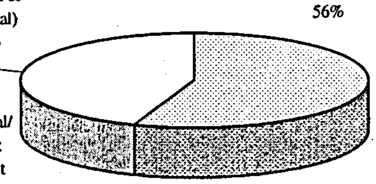


Figure 4-5 Requesting information channels (contractor' respondents)

Requesting information channels: Channels are the conduits through which the message flows. They can be formal, following organisational lines, or informal with virtually any structure. Figure 4.5 shows the most common channels used by contractors to issue requests for information. Fifty-six percent of respondents stated that they use formal channels to issue requests for information. Forty-four percent of respondents use both formal and informal channels to issue requests for information. No respondent relies solely on informal communication channels.

<u>Communication adequacy between contractors and designers</u>: Sixty-six percent of the contractor respondents assess the communication adequacy between them and designers as 'fair' with regard to obtaining the necessary information to perform their job. Only 28% consider it 'good' as shown in Figure 4-6.

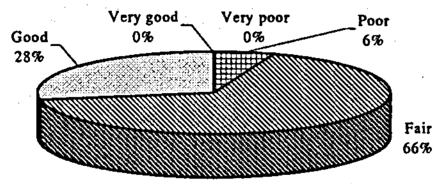


Figure 4-6 Communication adequacy (contractor respondents' view)

<u>Conflicting instructions</u>: Receiving conflicting instructions from designers is a common problem in construction. Eighty-nine percent of the respondents had 'sometimes' experienced this during the construction stage (see Figure 4-7).

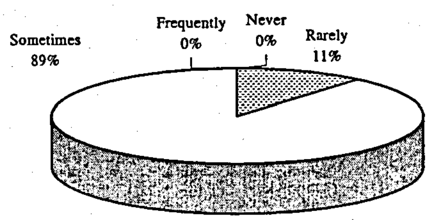


Figure 4-7 Receiving conflicting information (contractor respondents)

<u>Collaboration between construction and design teams</u>: Construction and design teams may need to collaborate to solve design problems, which arise during the construction stage. Figure 4-8 reveals that 100% of respondents 'Sometimes' to 'Frequently' collaborate with design teams to solve deign problems that they face during construction.

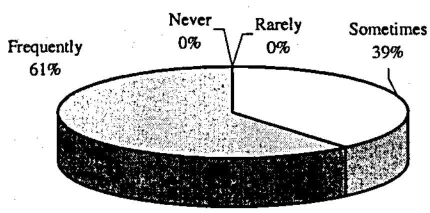


Figure 4-8 Collaboration with design team in solving design problems (contractor respondents)

<u>Effect of visualisation on communication</u>:

The contractors were asked about their opinions on visualisation and whether it can improve communication during the construction stage. Approximately 95% of the respondents are of the view that visualisation can improve communication during the construction stage (see Figure 4-9). The respondents who replied 'much' or 'very much' to this had some time used one of the computer visualisation tools in communication.

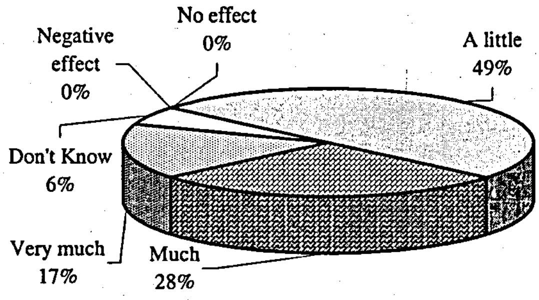


Figure 4-9 Effect of visualisation on communication during construction stage (contractor' respondents view)

4.2.8 Consultants View/ Perspective

<u>Visualisation Tools</u>: Consultants were asked about the use of computer visualisation tools at each design stage (see Table 4-8). Sixty-four percent of respondents 'Sometimes' to 'Frequently' use 3-D models at the conceptual design stage while 55% of them use 3-D models in presentations. Other visualisation tools such as rendered images, animation and VR/VRML have relatively low usage.

Table 4-8 Visualisation tools used by consultant' respondents

	3-D CAD Models	Rendered Images	Animation	VR simulation	VRML presentation
Conceptual design	64%	45%	27%	0%	0%
Detailed design	36%	9%	0%	0%	0%
Services design	27%	9%	0%	0%	0%
Design analysis	45%	0%	0%	0%	0%
Production Information	36%	0%	0%	0%	0%
Presentation	55%	36%	27%	0%	0%
Project planning	27%	0%	0%	0%	0%
Collaboration	27%	9%	0%	0%	0%
Communication	9%	9%	18%	0%	0%

<u>Communication techniques:</u> One hundred percent of consultants in the survey use e-mail at the detailed design and production information stages. Electronic data transfer

is used by 91% of respondents at the conceptual design and production information stages. The Internet and Intranet are used by 82% at the production information stage. From Table 4-9 it can be seen that e-mail, electronic data transfer, and the Internet and Intranet have had a high level of usage at different stages. Video Conferencing and Virtual Reality are only very rarely used by respondents.

Table 4-9 Communication media used by consultant respondents

	Conceptual design	Detailed design	Service design	Production information	Project Planning	Communi-cation
E-mail	36%	100%	73%	100%	9%	9%
Video Conferencing	9%	0%	0%	0%	0%	0%
Electronic Data Transfer	91%	73%	55%	91%	45%	55%
Virtual Reality	0%	0%	0%	0%	0%	0%
Internet/ Intranet	73%	55%	64%	82%	27%	45%

Buildability problems Figure 4-10 shows that 64% of consultant respondents experience problems with the interface between the components of the frame, stairs, cladding or mechanical installations. While fifty-five percent of respondents

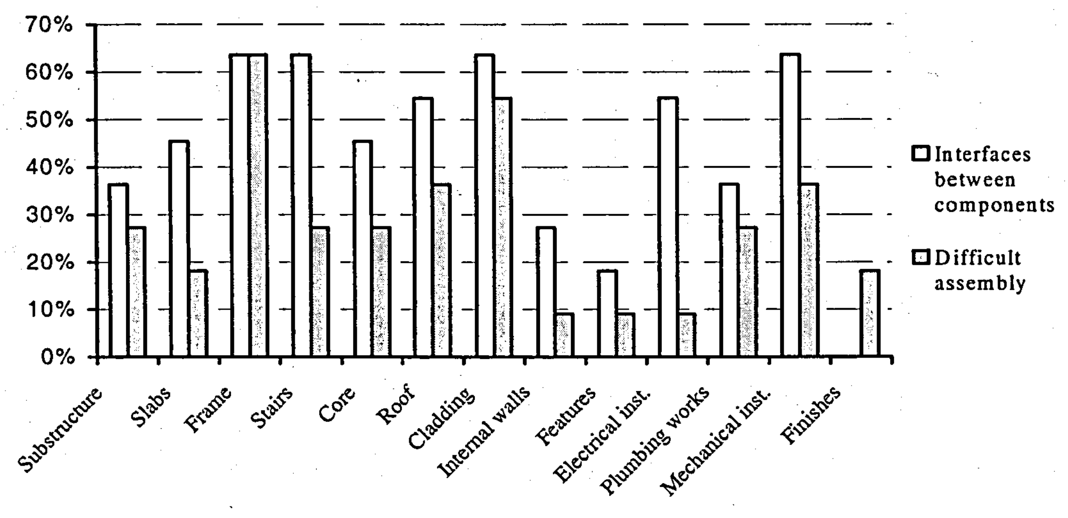


Figure 4-10 Buildability problems (consultant' respondents view)

experience problems associated with interfaces between components of stairs and electrical installations. Similarly, sixty-four percent of respondents experience assembly problems with the frame. The other buildability area associated with difficult assembly (as experienced by 55% of respondents) is cladding. The respondents regarded the remaining building parts such as substructure, slabs, and core as less problematic areas.

Reasons for buildability problems: The causes of buildability problems vary from one buildability area to another. Conflicting design information is regarded by 73% of the respondents as the most frequent cause of buildability problems for stairs, and by 55% of the respondents for substructure, slabs, core, and cladding. Another major cause of buildability problems is the lack of experience in reading design drawings; this is highlighted by 55% of respondents. The remaining causes are regarded as relatively infrequent (see Figure 4-11).

Methods used to clarify design details: Table 4-10 shows that the most common methods used to clarify design details were conventional methods i.e. written statements, 2-D drawings and face-to-face meetings. Computer visualisation such as 3-D models and presentations on the Internet are used occasionally. Rendered images are no used at all.

Table 4-10 Methods used by consultant' respondents to clarify information

	Written Statements	2-D Drawings	Physical models	Face to face meetings	3-D Models	Rendered Images	Video Animation	4-D CAD	VR	VRML	Presentation on the Internet
Substructure	82%	82%	18%	73%	9%	0%	0%	0%	0%	0%	9%
Slabs	82%	82%	18%	73%	9%	0%	0%	0%	0%	0%	9%
Frame	82%	82%	18%	73%	9%	0%	0%	0%	0%	0%	9%
Stairs	82%	82%	18%	73%	9%	0%	0%	0%	0%	0%	9%
Core	73%	82%	18%	73%	9%	0%	0%	0%	0%	0%	9%
Roof	73%	82%	18%	73%	9%	0%	0%	0%	0%	0%	9%
Cladding	73%	82%	9%	73%	9%	0%	0%	0%	0%	0%	9%
Internal Walls	73%	73%	9%	73%	9%	0%	0%	0%	0%	0%	9%
Features	64%	73%	9%	73%	9%	0%	0%	0%	0%	0%	0%
Electrical Installations.	64%	73%	9%	73%	9%	0%	0%	0%	0%	0%	0%
Plumbing Works	64%	73%	9%	73%	9%	0%	0%	0%	0%	0%	0%
Mechanical Installations.	64%	73%	9%	73%	9%	0%	0%	0%	0%	0%	0%
Finishes	64%	73%	9%	73%	9%	0%	0%	0%	0%	0%	0%

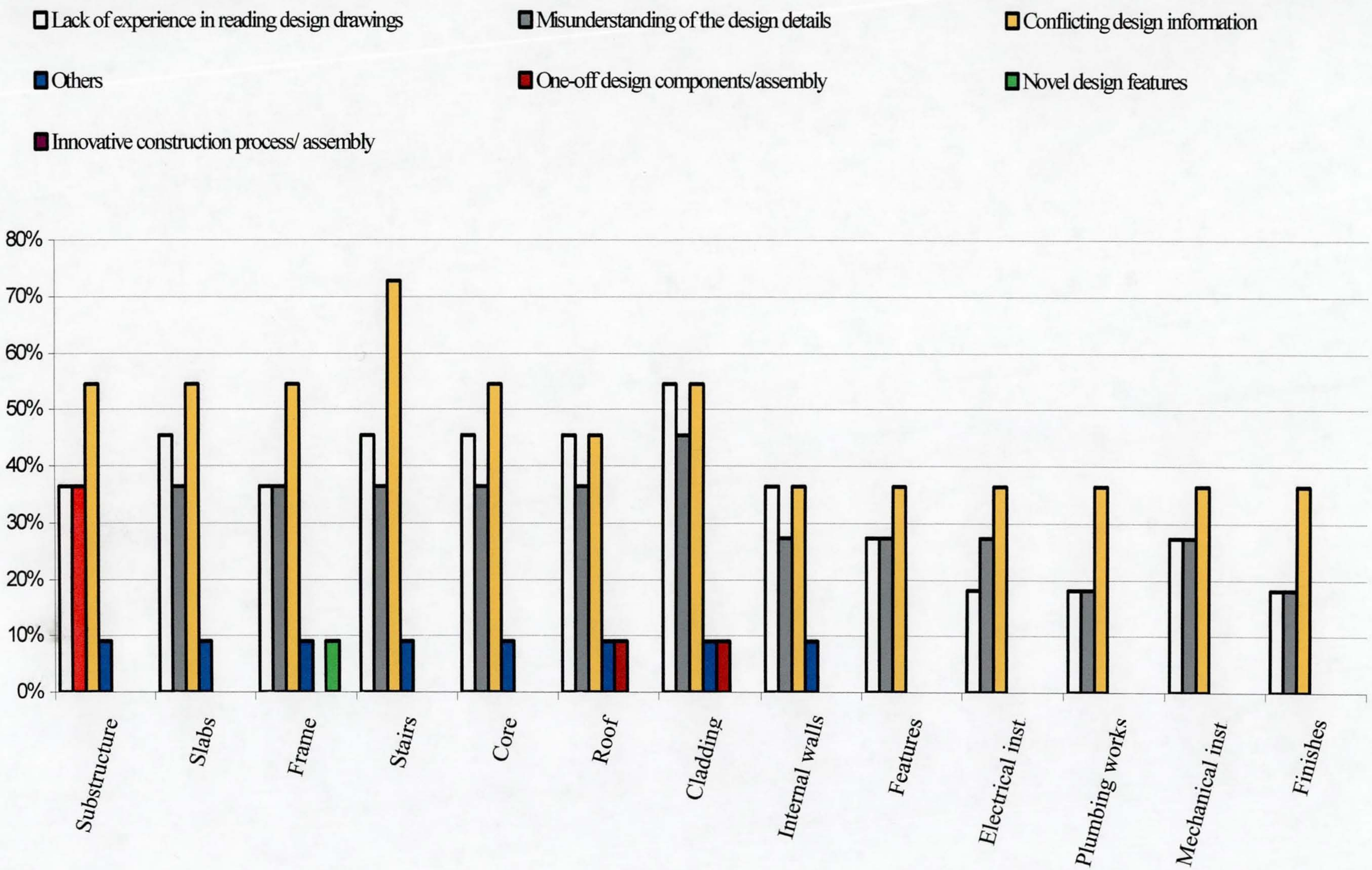


Figure 4-11 Buildability problem causes (consultant respondents view)

<u>Ensuring contractors' compliance with design details</u>: Contractors may need to recommend or make changes to some design details. The consultants are asked how often they ensured contractors' compliance with their design details, 91% stated that they do this frequently (see Figure 4-12).

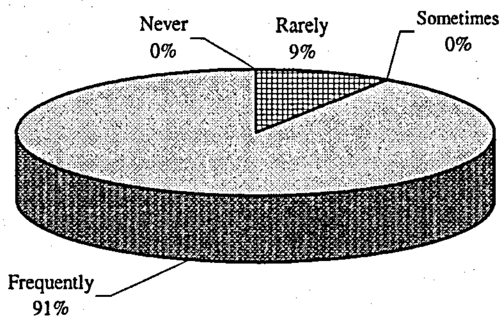


Figure 4-12 Ensuring contractors' compliance with design details

<u>Collaboration with the site team in solving design problems</u>: Consultant respondents are asked how often they worked with the site team in solving design problems that arise on site. Eighty-two percent (see Figure 4-13) of the respondents stated that they frequently work with the site team to solve problems.

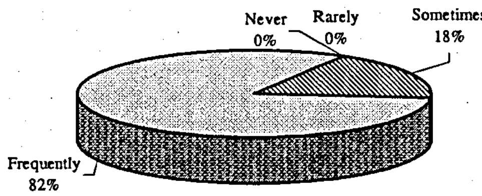


Figure 4-13 Collaboration with site team

<u>The possible effect of computer visualisation on communication</u>: Figure 4-14 shows that 82% of the respondents think that computer visualisation can improve (to varying degrees) communication during the construction stage of a project. Eighteen percent of the respondent think that visualisation can improve communication 'very much'. The respondents who stated that visualisation can improve communication 'much' or 'very much' are mainly those who use one of the computer visualisation tools at some stage of the design process.

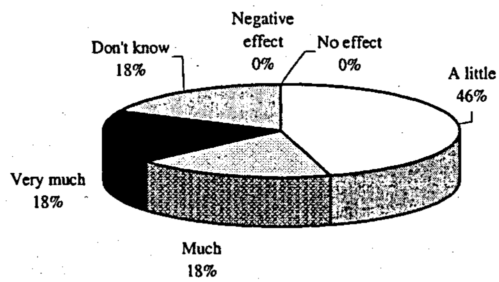


Figure 4-14 Possible effects of visualisation on communication (consultant respondents'view)

4.2.9 Discussion

Although the use of computer visualisation tools by consultants during the conceptual stage was common, this use was only for presenting the design concepts to the clients;

it did not go beyond that to cover for example the analysis of design alternatives. Indeed 3-D models and walkthroughs are good visualisation models to illustrate buildings before they are built and present the design to lay people who have no experience of reading architectural drawings; they can also be good design and communication tools. Designers are not usually pushed by clients to use computer visualisations to communicate their designs to others in the team resulting in a reluctance from them to undertake tasks they are not paid for. Furthermore, computer visualisation tools were not used in other design stages especially at the detailed design stage to communicate design intent to others. The low usage of computer visualisation tools by contractors is perhaps due to them not being involved in design unless it is a design and build contract.

The very low usage of computer visualisation as a communication tool by consultants result in its use by contractors being very rare. Contractors may need computer visualisation to help them better understand the design intent, this however should be led by design team. Contractors cannot benefit from the use of computer visualisation unless designers introduce them.

Lack of skill and training preference for paper work and a perceived lack of investment in the necessary facilities are seen as the main obstacles for adopting computer visualisation tools. The high cost of creating 3-D visualisation (the cost of software, hardware and labour) is also seen as an obstacle to the use of computer visualisation. Another important reason could be related to the fact that decision-makers in design organisations are not aware of what the new technology can provide them with, especially computer visualisation tools, as these usually come from paper-based schools.

E-mail and data transfer are used by consultants to communicate with others, particularly at the detailed design stage as these media are tools for exchanging information and drawings with other design participants. The detailed design stage is information-intensive and this information sometimes needs to be transferred and distributed very quickly between all design participants, such as architects, structural engineers, and services engineers. The use of e-mail and data transfer will ensure that all participants receive the latest information on time to avoid any delays caused by lack of information. It addition, e-mail and data transfer are cheap, fast and secure. For the above-mentioned reasons and others, e-mail and data transfers are the most widely used communication media in the construction industry. From this it can be concluded that the construction industry has the capability to adopt new technologies that provides them with direct savings in cost and time. Also in developing any system for communication, these technologies should be taken into consideration.

Interfaces between components are regarded by both sets of respondents (contractors and consultants) as more problematic than difficult assembly associated with most buildability areas. Mechanical installation is the most problematic area especially with regard to interfaces between components. These problems are usually the result of the lack of co-ordination between services designers and other designers in a construction project. Cladding was also found to be a problematic area. Both contractors and designers found the interfaces between different types of cladding and other building components a major buildability problem. Both contractors and consultants had problems with interfaces between stairs and the other building components related to them. The problems are, for example, that the stair does not fit within the stairwell or the height of the stair does not meet the height of the slab. Other buildability areas are found to be less problematic but to varying degrees. Nevertheless, the industry postal survey did not show whether these buildability problems vary from one project to another i.e. a buildability problem, for example, where cladding in one project differs from that in another project, or not. These problems should be discussed in more detail with the interviewees to check whether they are always the same or whether they differ from one project to another.

Both contractors and designers consider conflicting design information as a major cause of most buildability problems. The lack of proper communication tools and co-ordination in design information causes conflicting information in the design of a project. Services design is always the last part of the detailed design stage leading to other design disciplines not taking into consideration services provisions. Therefore, conflicts between services and other building elements are common. According to contractors, another major cause of buildability problems is poor design detail. On the other hand, designers (consultants) blame contractors for not possessing adequate experience in reading design drawings. Designs should be well represented so that even people who have little experience can understand the design intent. As mentioned earlier, designers use computer visualisation such as 3-D models and walkthroughs to show their design to clients. Designers represent their designs in a way they think that others can understand easily them, however, this is not always possible. Moreover, just because contractors cannot always understand design drawings this does not mean that they do not possess the skills needed for reading design drawings. Computer visualisation tools may help in this situation and therefore one group (designers) cannot blame the other group (contractors) for misunderstanding the design.

The most common methods and tools used to clarify design details between designer and site-teams are the traditional ones such as 2-D drawings, face-to-face meetings, written statements and the use of a telephone and/or fax. Designers and contractors are accustomed to these methods and tools and find them easier to use which do not require special skills. However, as discussed earlier, these methods and tools were not considered adequate and fast enough in communicating requests for information and for requesting clarifications on some designs.

The higher usage of formal channels over other channels ("informal", and "formal and informal") by contractors in requesting information may be one of the causes of delays in getting information. Formal channels follow the chain of command established by an organisation hierarchy of authority. For example, an organisation chart indicates the proper routing for official messages is by passing from one level or part of the hierarchy to another. Because formal channels are recognised as authoritative, it is typical for the communication of policies, procedures and other official announcements to adhere to them. Informal channels do not follow the chain of command. These informal channels coexist with the formal channels but frequently diverge by skipping levels in the hierarchy and/or by cutting across vertical chains of command. An excellent organisation is an organisation with a vast network of informal and open communication.

Contractors and consultants, who had used computer visualisation or any one of its applications at any stage of design or construction process, realised the benefits that could be gained from the use of visualisation in improving communication in construction, particularly between the design and construction teams. Generally, contractors suffer more problems caused by the lack of proper communication media and tools.

The industry postal questionnaire survey gathered a considerable amount of information for the research project. At the same time, it highlighted several issues to be investigated in more depth. Case study interviews, therefore, are needed to investigate these raised issues.

4.3 IN-DEPTH INTERVIEWS/CASE STUDIES

To achieve integration, each stage of the research (i.e. literature review, questionnaire surveys and in-depth interviews) was fed into and reinforced the next stage. Consequently, the results of the questionnaire formed the basis for selecting construction contractors and designers for case study interviews. It was decided to use a semi-structured to encourage in depth discussions and greater interaction with interviewees. The main problem lies in the interpretation of the data collected, as it is generally unsystematic or unstructured. The interviews helped to draw together the salient information about visualisation and communication tools, and the buildability problems that a questionnaire alone could not capture.

Sample organisations were categorised according to the size of their turnover and whether they were considered primarily to be contractors or design companies based on their participation in the postal survey and willingness to participate in the research project. As mentioned earlier, the sample for the postal survey was drawn from the top 100 contractors and designers in the UK based on their ranking in the New Civil Engineer (NCE, 1999). The time constraints and availability of professionals to be interviewed restricted the number of interviews to eight. The case study firms consisted of four companies considered to be primarily contractors and four companies considered to be primarily designers.

4.3.1 Objectives of the Case Studies

The case studies' objectives were:

- develop an in-depth understanding of attitudes and perceptions of the industry professionals involved of the use of design information related to buildability;

- obtaining more information on issues that arose from the analysis of the postal questionnaire;

- identify examples of buildability problems that may be used in the prototype system;

- establish whether buildability problems are the same in most projects or differ from one project to another; and

- explore the functionalities and features that needed to be incorporated into the prototype visualisation and communication system.

4.3.2 Methodology

To achieve the objectives of the case study interviews, contacts were made by sending letters to the organisations. Later, telephone calls were made to arrange the date and time of the interviews. Details of the organisations involved in the case study interviews are summarised in Table 4-11.

A semi-structured interview template (see Appendix C) was sent to specific individuals in the organisations. Interviews provided insights into the views of construction contractors and designers views about the possible use of computer visualisation for communicating buildability information in the construction industry. The interviews used well-established semi-structured techniques intended to minimise any interviewer bias. The researcher was conscious of avoiding prejudice stemming from either the researcher or the interviewee. The bias was also diminished by open and non-leading questions (Easterby-Smith et al. 1991). Each interview lasted between forty-five minutes to one and half-hours. All interviews were conducted with project managers and recorded on audio-tapes.

Table 4-11 Type of Organisations invloved in the case study interviews

Organis-ation	Type of business	Turnover	Employee
A	Contractor	£400 M	745
B	Contractor	£428 M	1320
C	Contractor	£457 M	750
D	Contractor	£1065 M	3588
E	Consultant	£5.4 M	218
F	Consultant	£19.06 M	495
G	Consultant	£43 M	819
H	Consultant	£6.76 M	138

4.3.3 Results

The following is a summary of the issues raised during the interviews. These are the interviewees' responses to questions and comments only.

4.3.3.1 Organisation A

Background

This is an international construction company with a turnover of approximately £400M which employs approximately 745 employees.

Visualisation and Communication Tools

The most common visualisation tools used within the organisation are rendered images and 3-D CAD models for fly-through animations. Other visualisation tools such as VR and VRML are not used because there are no financial gains from doing so; for example, no direct cost savings that would result from their use.

The infrastructure for computer communication is on site where e-mail is available (an internal e-mail system). Video conferencing is not widely used for communication mainly because the organisation is not set up for it. Video conferencing would be helpful as the organisation has several offices spread around the country. VR has not been used in the past; this is because the organisation's previous computer system was very slow. However, the organisation has never been asked to provide VR models. In future, VR may be used as a marketing tool.

On new jobs, the organisation has Internet access and a central Web site for drawings to enable the site teams to view and comment. These comments are then sent back to the architect or whoever is entitled to access the drawing. The provision of Internet access from all sites can be seen as offering cost benefits as well as a means of eradicating reams of waste associated with paper-based drawings and documentation.

Buildability problems and their causes

There are not many buildability problems associated with the substructure. Most buildability problems are to special features which tend to be very badly or inadequately detailed. These poor design details may lead to ambiguity. Furthermore, the architect wants to develop special features as much as possible and, therefore, the information comes through to the site too late. The problems encountered with stairs are mainly due to work schedules. Problems of poor design details may appear because of too little time being dedicated to the detail design process where infrastructure is not checked thoroughly. Therefore, when the stairs arrive on site with one thread extra, or being too long or too short then they do not fit properly.

Interfaces between different types of cladding are also sometimes problematic. This problem is mainly caused by poor design detailing.

The major buildability problem with services installations are the clashes between them and other components in the building. Services installation problems are usually caused by poor co-ordination between them and other components in the building. Problems frequently occur in roofs. This is because they are often quite large so when two roof are joined together, they do not always fit. It is in this situation that the detailing (such as gutter details) tend to be very poor and defects occur. This type of problems usually exist where there are special features.

The major causes of buildability problems are conflicting design information and poor design details. If the services, for example, have to run through openings in the beams and the opening size is not sufficient, these services will then be redirected to run underneath the beams. This leads to changes in the design of other parts of the building and causes problems such as inadequate headrooms. Inadequate specifications are also one of the major causes of buildability problems. Quite often, the client does not have a clear idea about cladding or roof types. Consequently, some of the specifications the contractor gets are very poor in terms of defining exactly what the client wants. This also applies to service installations.

Information exchange and collaboration

Requests for information are put on the organisation's building management system (this is the document the staff will follow and which contains instructions on what to do) using certain forms for RFI (Requests for Information) and CBI (Confirmation of Building Instructions). There are different routes to follow for information exchange and the choice of the route depends on the job and the situation. On traditional jobs for example, where the architect acts as a co-ordinator, all the information goes to the architect who passes it to other parties. However, in most cases the architect will manage the construction and design process.

There are weekly, fortnightly, or monthly regular design team meetings to ensure the work is going as planned and to discuss any problems. There are also informal discussions over the telephone with the design teams, and other related construction participants, to discuss solutions to any problems that occur during the construction stage. As a contractor, the site teams always work with designers and participate in the design, so the design team can benefit from their experience.

4.3.3.2 Organisation B

Background

This is an international construction company with a turnover of approximately £428M which employs approximately 1320 employees.

Visualisation and communication tools

Computer Visualisation tools are not widely used within the organisation. Professional opinion in the organisation is that visualisation tools are not useful at the tendering stage, however, they would be more useful for the other stages. E-mail was widely used within the company as well as in communicating with other companies such as consultants. However, there are still some organisations that have not yet adopted e-mail as a communication tool.

In the last 12 months the organisation has become increasingly successful. There are still many consultants who do not have the facilities to do what the organisation wants them to do. The organisation tends, therefore, to be very selective of its consultants. If an architectural firm, for example, does not have the necessary technology, it will not be selected for the job. For instance, one of the obstacles which prevents the use of e-mail by the organisation is that there are organisations such as Quantity Surveyors who do not have the facilities to print out CAD drawings.

Buildability problems and their causes

There are several buildability problems that arise during the construction stage. There are usually problems with stairs. These are problem which require thinking in 3D, which is problematic for many people. On a number of occasions, the organisation has found that stairs would not fit into a stairwell as the stairwell was too small. The interviewee believes that 3D visualisation would certainly be helpful in this respect.

Regarding cladding, currently there is a number of different types of cladding on the market that needs to have secondary steelwork in the right place in order to hold the different bits of the cladding. This is done to avoid flying edges of cladding that do not have anything behind. This could also be solved 3 dimensionally. Curved roofs, are another example of buildability problems. The problem is how to detail the edge of the roof and make it all watertight. Building services are another major area where buildability problems are experienced. In most cases, there are clashes between building service installations and other components, an example is where the depth of ceiling void is not sufficiently deep to run the services.

Misunderstanding design details is another cause of buildability problems. If design details are not clearly outlined, assumptions are made, these assumptions are not always correct. If design details were drawn in 3-D, it would be much easier to understand the design intent. Conflicting design information is also a big contributor to problems on site. The architect makes an assumption on certain aspects of the design while the structural engineer makes a different assumption. Lack of proper communication can result in assumptions, this in turn can make the design based on inaccurate information. Therefore, when the design details are passed on to the contractor, they include conflicting information and problems arise during the construction stage.

Information exchange and collaboration

Information related to buildability is requested through a fixed system, this system is known as RFI (Request for Information) on pre-printed forms. The main drawback of this system is where there is a misunderstanding between the sender and the respondent. Therefore, the question has to be formulated very carefully otherwise the answer could be incorrect. One of the reasons for recommending a change to some design details during construction is that some of these are impossible to construct.

4.3.3.3 Organisation C

Background

This is an international construction company with turnover of approximately £457M which employs approximately 750 employees.

Visualisation and communication tools

E-mail is the most common communication tool within the organisation. It is available in all the organisation's offices and on most of the larger sites. Electronic data transfer is available at Head Office. Computer visualisation as a communication tool is not used. The main reasons for not using computer visualisation as a communication tool is the lack of resources and understanding of what computer visualisation can provide. The organisation believes that as a contractor it is not in a position to develop a complete visualisation, the designers should use it to enable them (constructors) to understand how the design product can be produced.

Buildability problems and their causes

The most problematic area are services installations. Lack of co-ordination between design teams is the main cause of problems. Different types of cladding which join at one point are also problematic. The main problem is how to make the joints watertight. The roof is usually another problem area. There are difficulties associated with understanding a 3-D pitched roof on a 2-D drawing. If a 3-D model or isometric drawing of a roof system were produced, it would be much easier to understand how the roof will look in reality.

The buildability problems with stairs occur at the floor levels. The problem is that there are finished floor levels and structured floor levels. Different designs will not take into account the finishes that have been specified by the architect and likewise.

Poor design details are regarded as a major cause of buildability problems. The designers do not sometimes think about the input and output of all the detailing. They lack the experience of how to put a building together and do not understand the construction technology or buildability aspects.

Information exchange and collaboration

Requesting information is carried out by filling in a technical Query Sheet, detailing the problem and faxing it to the designer. The answers are sometimes in a written statement form. Written answers are not always easy to understand and need to be supported with a further sketch or detailed drawing. It is difficult to make the design team understand the problem or the query using this method. The design team may need to visit the site to look at the problem. This process delays the construction of a project and the length of the delay depends on how complicated the problem is.

4.3.3.4 Organisation D

Background

This is an international construction company with a turnover of approximately £1065M which employs approximately 3588 employees.

Visualisation and communication tools

The main visualisation tool used is animation, however, this is used as a sales tool to demonstrate how a development will look. Animations are not viewed of as a practical tool for conveying detailed design, as they are too expensive to produce. The organisation has just begun to use 3-D models and have found them useful especially in relation to complex services. However, 3-D models are still in their infancy and their use will increase significantly.

E-mail is a good communication medium where complex documents can be sent electronically at low cost. Video conferencing was found to be not as effective as face-to face meetings. However, they save time and travelling expenses so it is therefore also a cost effective method of communication.

Buildability problems and their causes

Interface between components is problematic and occurs when non-standard components are used or where putting components together in an unusual way. There are always problems in interfaces between components of cladding and mechanical and electrical installations in particular, as they tend to be more complex systems. Cladding used by the organisation in the majority of buildings is to some extent a bespoke system where there are new and unique features in every project.

In the interface between building components and the structure it is quite often an issue of not understanding the tolerances or not understanding the potential deflections. Sometimes it is a direct interface between one component and another where there is a complex geometry. There is frequently a problem if the building is not rectangular. There are also problems with interfaces between cladding and other building components that lead to water leakages.

Poor design details are a major cause of buildability problems. These occur because specialist contractors are often not brought in early enough. Therefore, as architects and/or engineers cannot be expected to understand these problems, specialists need to be consulted during the early stages of the design process. Other difficulties arise from not understanding how different components fit together when two-dimensional drawings are used.

Information exchange and collaboration

Designers are getting better at collaboration and they realise the need to involve contractors. In practice, collaboration is an aspect where the whole industry is improving. Many clients realise the importance of collaboration and encourage designers and contractors to collaborate more effectively through discussion and communication. It is the best way to reduce buildability problems.

4.3.3.5 Organisation E

Background

This is an international design company with turnover of approximately £5.4M which employs approximately 218 employees.

Visualisation and communication tools

The use of computer visualisation tools is limited because of expectations and tradition. Electronic data transfer is usually used to transfer drawings and documents between the organisation's offices and others who participate in the design process of a project.

Buildability problems and their causes

This organisation is different from others because it does not work exclusively, most of its clients are actually contractors. Therefore, after the design has been done, the contractor will immediately comment on the design. Designs tend to be changed several times ahead of construction and often once the construction process has been discussed, it still has to be modified to suit the contractors' methods. If something has been built incorrectly, it is usually accepted and the design is then modified according to what has been built. This is always cheaper than demolishing the completed work. These situations are usually the result of contractors not understanding the design or omitting some of the design details.

Contractors may complain that certain elements of the design are unbuildable or very difficult to build. This is regarded as a problem by the organisation as they aim to make all their designs buildable. However, in these situations, the designs can be modified to enable construction to go ahead. Critical activities that need some attention during construction are usually identified by spending more time and taking more care over design details.

Information exchange and collaboration

Many contractors benefit highly from having the designer present and this allows them to explain design details. The contractor can, therefore, make a decision to raise, technical queries and/or make Requests for Information. It is quite common to receive conflicting design information from other designers. This is mainly caused by a lack of proper communication between either the design teams or within the design team itself.

Contractors usually participate in design problem solutions. Generally, a meeting between some members of the design and contractors teams is arranged on site. As the organisation is designing predominantly for contractors they prefer to talk to contractors on site to resolve problems. The other way of collaboration is over the telephone. Participation by contractors at an early stage of design is needed to understand the balance between speed of construction and economy of materials. Therefore, it is of importance to communicate with contractors at an early stage of the design process.

4.3.3.6 Organisation F

Background

This is an international consultant any with a turnover of approximately £19.06M which employs approximately 760 staff.

Visualisation and communication tools

The organisation found the use of 3-D models as a visualisation tool very useful, particularly in terms of demonstrating to the client what they believe to be a concept design, thus obtaining approval of the design. VR is regarded as being too expensive to use. E-mail is used extensively within the organisation, it is found to be a very useful communication tool, undoubtedly because of its speed. The Internet is an effective tool for sending drawings and images, across the world, thereby overcoming courier problems that have sometimes occurred. It also shortens the time-scale relating to getting hard copies of documents from one place to another.

Buildability problems and their causes

Communication is regarded as the major cause of the buildability problems which occur during the construction stage of a project. The interviewee believes that If all the issues that effect any one problem were available and known by all parties at the same time, then there is an opportunity for all those issues to be discussed and the problem being solved.

Conflicting information and misunderstanding of the design details were regarded as other major causes of buildability problems. This was notably because of the lack of communication between all parties involved in the design process. The most important is to get the design right. Making changes to the design is common process, what is to take into consideration the effect of the changes in one part of design on another part. The organisation believes that one of the solutions to conflicting design information is either the use of computer visualisation or standardisation in building components

Information exchange and collaboration

Requesting information can be done in different ways; it depends mainly on the construction area (civil engineering or building). In civil engineering there are usually significant supervision resources on site and the requests come in written form, this is too simplistic. If there is a problem, the first step is to make a request for information, this should be in a written form and is sent either by fax or through the mail. The main problem with this process is in describing the problem and any other related issues.

Collaboration between contractors is conducted at three levels. The first level of collaboration occurs day to day between people who are closest to the work so problems may be solved as they occur on site. If the problems cannot be resolved at this level, they are then raised to the second level and will be discussed at a progress meeting. Finally, the new form of collaboration the organisation is planning to introduce is contained within the contract itself. This is achieved at senior executive level, where senior partners discuss the progress made by the various contractors employed on the site.

4.3.3.7 Organisation G

Background

This is an international consultant with a turnover of approximately £43M which employs approximately 819 staff.

Visualisation and communication tools

Computer visualisation tools are not used within this organisation. Computer communication tools, except e-mail and data transfer, are also not used. There are several reasons for not using these tools, these are: the high cost of software and the cost of producing computer visualisations for a proposed facility; construction professionals regard computer visualisation as a tool for selling product designs rather than a tool for solving problems; decision-makers are people who probably came up through the paper and hand drawing schools, therefore, they are less keen on adopting new technology.

Buildability problems and their causes

The organisation, as a design consultant, does not face problems in buildability. Problems with stairs can be avoided by understanding and knowing the tolerances. The problem with stairs from the structural side is that they do not fit within the stairwell. This happens if the stairs are built incorrectly but this is just a site-setting problem. Theoretically, this should never happen because on the majority of contracts the architect is responsible to the client for the co-ordination of design of all disciplines. In reality, the basis for the design of a building is the architectural drawings and none of the other design disciplines can alter the whole or any part of these drawings. The contractor, therefore, will follow these drawings. So if there are any buildability problems, it is only because the architect has drawn it incorrectly and this can be attributed to basic human error. Any error should be recognised during the checking process.

There were some problems associated with roofs, one of these was in a curved roof. The dimensions on the architect's drawings were, instead of being a constant radius all the way round, had a different radius over the top segment. Another problem with roofs occurs when multiple curved roofs meet and are co-jointed. There are difficulties obtaining the correct alignment of joints where they occur. This affects the amount of time required by construction teams involved in the installation of the roof.

In design and build projects the company providing, the cladding is involved from the first day of the design stage. If it is a traditional contract, usually the architects discuss details such as, around window heads, finishing off drips and any other related issues related to perforations of the cladding, with the cladding subcontractor. The selection of cladding is part of the architect's duties. If different types of cladding are selected, the architect should discuss the cladding design with one cladding firm rather than with each part of cladding provider and finding out which parts are incompatible. Problems with interfaces between cladding and other building components are usually caused by poor detailing.

In the past, the design staff spent three or four days tracing the architect's drawings from a copy negative. This would stretch slightly as it went through the printer so there was a need to calculate all the dimensions to ensure accuracy. The electronic exchange of information from the architect to other design disciplines has been beneficial in co-ordinating all the design information as all the different design disciplines are working from the same model. This base model must be precise in dimensions and all the information contained in it must be accurate; otherwise the base model will be useless and lead to conflicting information. If conflicting information occurs at the construction stage, the design will usually be modified to fit.

Written statements are unlikely to help buildability. They were used once within the organisation and that was for a project that had special type of flooring. The written statements where used to ensure accuracy of the construction sequence. They did not contain any specifications but were used more to protect the organisation. For general buildability problems, 2-D drawings are used to clarify any information. If a problem occurs, face-to-face meetings, discussing and viewing the problem, drawing it on the structure concerned to see how it could be redesigned, may resolve the problem. In one of the projects the organisation was involved in, the contractor set a retaining wall that was part of a sub-structure to a building incorrectly. The contractor confused the architect's grid lines with column centre lines. For some reason the columns were not on the grid. The engineers went to the site and draw it out on the structure, studied the problem physically, and resolved it.

Information exchange and collaboration

Information is usually requested by and from the organisation by filling a form containing questions that need to be answered. There is always difficulty with these, particularly with contractors being given unreasonable deadlines. Besides formal communication routes, informal routes are used as they are regarded as the best way of solving problems. This allows the contractor to collaborate and break down the barriers between design and construction teams. Filling in a form or writing a request for information, sending a fax or email; waiting for a reply takes a long time compared with communicating by telephone to ask the question and obtaining an immediate response.

4.3.3.8 Organisation H

This is an international consultant with a turnover of approximately £6.76M which employs approximately 138 staff.

Visualisation and communication tools

The use of 3-D models within the organisation is basically to understand completed structures and gain a general perspective. Designs are also modelled in 3-D to understand how structures come together. This is not the case with every design, but done when the design is too complicated, and a 2-D drawing is not an adequate tool for visualising the part of design to evaluate or study. It actually depends on how complicated the problems and the structures are.

E-mail is the most commonly used method of communication between the organisation, client and others. The organisation is developing its business using project hosting. This is storage or filing system where the design of a project and all related information are transferred to a Web site and all the people involved in the project have access to it.

Buildability problems and their causes

Buildability problems associated with cladding were caused by the construction process. Cladding is usually designed and erected by specialist contractors who are perhaps involved in the later stage of design process. Everyone in the design team has to make assumptions on what the cladding is likely to be unless the detailed design is specific. These assumptions are sometimes, although valid and constructable, not the most effective way for the cladder. As there is a competitive process where the cladder will be tendering with others; each one having a different way of fixing. Consequently, there is an interface where there is co-ordination; but problems are caused when assumptions are made and, therefore, compromise is called for, instead of each contractor continuing on their own detail or working around what they assume is wanted.

The buildability problems are different from one project to another and they depend on the personnel involved. In the same practice, for example, there are some designers who are experienced more than others; consequently they produce information that is quicker and easier to do it. Lack of experience in reading drawings can be seen as one of the causes of buildability problems.

Conflicting design information related to, for example, stairs, causes problems in erecting or fixing building components together. For instance, problems where in, the architectural drawings turn out to be not physically constructable. Therefore, the complexity with other designers' drawings (e.g. structured drawings) which are made up of assumptions lead to a situation where the drawings do not match each other. From the architect's perspective the staircase is probably a minor part of the design. However, if these issues are not raised, problems may arise for other designers. This applies to cladding and service installations as well.

Information exchange and collaboration

The designer develops the drawings for contractors consequently they come back to the designer to discuss the design details on daily basis. Obviously the aim of the designer is to make drawings as simple as possible so nothing gets missed. There is obviously a checking process to make sure that if anything if missed it would be picked up and rectified. Contractors usually ask about clarifying some design details. This tends to be done by telephone rather than studying drawings. It is much easier for a contractor to ask the relevant question ring someone and say: "What are you trying to achieve with that detail?" Rather than trying to work it out from a drawing.

The organisation, as clients and other interested parties will find the use of technology advantageous over paper drawings. It would be possible to download any drawing and make the number of copies required. This saves time and all participants are aware of changes made to the drawings. This is something that the organisation is driving towards in order to improve the communication process in construction.

4.3.4 Summary of the results

The previous sections described the results of the case study interviews. Table 4-12 summarises these results in order to make it easier for comparison and discussions.

Table 4-12: Summary of the case study interviews

Organisation	Visualisation and communication tools	Buildability problems	Causes of Buildability problems	Information exchange and collaboration
A	• Rendered images • 3D Models • Fly through animations • E-mail • Internet	• Unique features • Stairs are with extra thread, too long or too short • Cladding • Services Installations have to run through openings in the beam and the opening is not sufficient • Two types of roofs are joined together	• Inadequate, conflicting and poor design details • Inadequate specifications • Work schedules • Poor-co-ordination between different building components • One off Design component	• RFI (Request for information) Form • CBI (Confirmation of Buildings instructions • The choice of the route for information exchange depends n the job and the situation • Regular meetings (weekly, fortnightly or monthly • Informal discussions over the telephone.
B	• E-mail is widely used as communication tools with other companies.	• Stairs would not fit into a stairwell • Different types of claddings join at one point • Curved roofs intersect with each other cause difficulty in doing the design details and get it all watertight • Clashes between services installations and other building components	• Misunderstanding design details leads to making assumptions • Conflicting design information • Lack of proper communication	• Pre-printed RFI forms which sometimes cause misunderstanding between the sender and the respondent • Recommending a change to some design details during the construction stage when these details are impossible to construct
C	• E-mail is available on the organisation offices and lager sites • Electronic data transfer is available at the Head office	• Service installations • Different types of claddings join at one point • Roofs • Stairs and floor levels	• Lack of coordination between design teams • Poor design details • Some designers lack the experience in construction	• Quarry Sheets • Written statements supported with sketches • Design team sometimes need to visit the site.

Table 4-12: Summary of the case study interviews (Continued)

Organisation	Visualisation and communication tools	Buildability problems	Causes of Buildability problems	Information exchange and collaboration
D	• Animations as a sales tool • 3D models are recently used • E-mail is widely used to send documents electronically • Video conferencing is rarely used	• Interfaces between components of cladding especially bespoke ones • Interfaces between components of electrical and mechanical installations	• Lack of understanding tolerance or the potential reflections • Poor design details • Lack of understanding how different components fit together from 2D drawings • Novel designs especially state of art buildings.	• Designers getting better at collaboration and the need to involve contractors in design • Formal communication routes are widely used to record of the matters discussed • Informal communication routes used when the matter is not so important
E	• Electronic data transfer is usually used to transfer drawings and documents	• Most of the organisation clients are contractors. Therefore, the contractor is involved from day one in the design and if there is any problem arise in the site then the design changed according to what has been built.	• Missing cross reference on the drawings • Misunderstanding or omitting of some design details	• There is usually one of design team is present on site to explain design details to the site team. • Contractors use technical queries • Contractors usually participate in design problem solutions • Meeting can take place on site to discuss the problem and possible solutions
F	• 3D models to demonstrate design concepts to clients • E-mail for communication • Internet to send drawings and images across the world	• Cladding • Services installation	• Lack of proper communication • Conflicting and misunderstanding of design information	• RFI form for formal information especially in civil engineering works • Telephone for informal communication • Collaboration with contractors conducted in 3 levels: day to day; progress meetings; and senior partners progress meetings

Table 4-12: Summary of the case study interviews (Continued)

G	• Email is widely used • Electronic data transfer	• Curved roofs • Interfaces between different Claddings	• Poor design details • Conflicting design information	• Formal communication by filling a pre-designed form • Informal communication routs using fax, e-mail • Informal communication routes seen as the best of solving problems • Informal communication routes allow design team to collaborate with construction teams and break down the barriers between the different design team disciplines.
H	• 3D models to gain a general perspective and how structures come together • E-mail is most common communication tool • Using the Internet as a project hosting where all related information are transferred and all people involved can access it	• Interfaces between services installation components • Interfaces between cladding and other components • Buildability problems differ from project to another	• Assumptions are the major cause of buildability problems • Lack of experience in reading drawings • Conflicting design information	• There is daily discussion between the design team and the contractor on daily basis • Informal communication route using telephone is quite common

4.3.5 Discussion

As discussed in Section 1.2.1, construction industry professionals need to consider the adoption of information and communication technologies that manufacturing industry have implemented. This industry differs from other industries in that its products are unique and prototyping is not possible except in housing developments. The adoption of technology may be costly in the short-term but it is required to keep up with advances other industries have achieved, especially as it has a reputation for low productivity, waste, low technology, and poor quality (Egan, 1998; Wakefield and Damrienant, 1999).

The low usage of computer visualisation tools can be attributed to several reasons. Some of the reasons have been mentioned earlier. The following are additional reasons found from the analysis of the case interviews. These are:

- Available hardware is inadequate for advanced visualisation;
- Lack of understanding and awareness among decision-makers in the construction industry of what computer visualisation can provide;
- Lack of well-trained CAD personnel who can produce computer visualisation models;
- The technology is changing very quickly so it is very difficult to keep up with it; and
- The high cost of producing good accurate models.

The above-mentioned reasons are not specific to the construction industry and can be found in any industry. Problems caused by fast changes in hardware and software requirements are common. The construction industry should consider the benefits that can be gained from adopting computer visualisation and communication tools. The decision-makers are not adequately aware about the benefits of these technologies because they come from paper-based schools and consider computer visualisation as an optional extra. A number of interviewees have tried to use computer visualisation on an individual basis to explore the possible benefits. These attempts were limited and inadequate to persuade the decision-makers in their organisations. These professionals realise that computer visualisation would help in conveying the design intent and mistakes can be avoided if 3-D models are created before construction starts. They believe that missing and conflicting information can be identified during the creation of a 3-D model of the proposed facility.

Buildability problems are not always the same in all projects. Buildability problems associated with cladding, for example, are not the same in all projects. Therefore, a library of standard cladding joints cannot be created for use in all project. Solving buildability problems can be achieved by the use of computer visualisation showing how a building component, with the high possibility of being problematic during construction, can be assembled and how the interfaces can be fixed.

The interviews conducted indicated that contractors believe that designers are not providing sufficiently clear design information, while designers believe that many contractors are not experienced enough to read design drawings. Computer visualisation can overcome this problem by creating a detailed 3-D model. This requires detailed information and enables anyone with little or no experience in reading design drawings to understand the design and its intent. Creating computer visualisation models for a whole building is time-consuming and requires a powerful computer. However, creating a computer visualisation for a specific part of a building that may be problematic to the site-team is not as costly and can be very useful for both the designer and the contractor. These visualisations result in considerable savings in time and cost. They can also be used as a basis for collaboration between the design and site teams in solving possible problems before construction starts.

Buildability issues, especially those related to assemblies and interfaces between building components are not given the same attention as other design issues such as specification and material quality. Failure to anticipate critical activities with potential problems on site is also a contributing factor to the delays and increase in costs caused by misunderstanding or requesting changes of design.

Site visits are sometimes needed to investigate problems that cannot be described using written statements. Designers need to arrange meetings with the site-team to discuss the problems and their possible solutions. The use of a Web camera or any other similar technology where the site-team can actually show the designers what the problem is before they have to travel to the site and can also interact with the designers remotely can save time in problem solving. The site-team can also take photographs and send them by e-mail or post them on a Web-site. Most interviewees considered face-to-face meetings as essential for solving design and construction problems. The use of video conferencing can help maintain visual contact, which many construction industry professionals regard as very important in discussions about construction and design problems.

Collaboration between construction practitioners is done on an ad hoc basis, as evident in the case studies, and needs to be better recognised as an important issue in the construction industry. The site-team's experience can be very beneficial to the design if brought in earlier during the design stage within a collaborative environment. Computer visualisation may help designers to collaborate with contractors to solve design problems. Adoption of new technologies, such as computer visualisation and communication, would do much to improve construction industry efficiency. However, one of the main barriers is that the industry is slow to uptake new technologies.

The findings of both the questionnaire and case interviews indicated that there are certain limitations on traditional visualisation and communication tools. These limitations cause many buildability problems and make communication between construction practitioners less efficient. The majority of these problems can be overcome using appropriate computer visualisation and communication tools during the design and construction stage of a project. Many of the buildability problems can be avoided using proactive three-dimensional models to investigate any possible problems the site-team may face and therefore find the solutions to them before building starts. A number of construction professionals realise what benefits the industry would gain as a result of more widespread use of computer visualisation. They realise that it can improve the transfer of design information correctly and on time. As discussed in Chapter 3, there is a need for a system for computer visualisations to support the communication and collaboration between the design and construction teams. The hardware and software are available but they need to be well structured and implemented to be used properly.

4.4 SUMMARY

This chapter has presented the results of the findings of an industry survey and case studies, conducted as part of this research. The survey provides a systematic examination of the experience and views of contractors and consultants on the use of computer visualisation for communication. The survey also included the buildability problems caused by the lack of proper communication tools and indicates that the use of computer visualisation was very low especially for communicating design information between designers and site-teams. The use of e-mail and data transfer was high and well established. As communication media in the construction industry, their benefits have become well known to the majority professionals. Buildability problems (interfaces between components and difficult assemblies) were widely experienced in areas such as cladding, roofs and service installations. Both the questionnaire survey and case studies, along with the findings of the literature, contributed to the development of the proposed visualisation system, which will be discussed in Chapters 5 and 6.

Chapter Five
Prototype system: conceptual model

CHAPTER FIVE

5 PROTOTYPE SYSTEM

5.1 INTRODUCTION

The last two chapters discussed the problems associated with information communication between design and construction teams during the construction stage. The lack of appropriate systems that may minimise these problems was identified. The focus of this chapter is to present the underlying conceptual model behind the development of a prototype system for information visualisation and communication during the construction stage. The model development takes into consideration issues that have been discussed in the chapters on information visualisation and communication, and industry perspectives on the role of visualisation in buildability.

5.1.1 Classification of Construction Information

Design involves the structuring of information concerning problems that are characterised as ill-defined. These ill-defined problems are often not known in full detail from the start of the design stage and therefore their structure cannot be presumed. Classification is a means to facilitate communication among the different parties in the construction field. It has considerable impact on the structuring of information that is essential in data exchange between the different participants in the construction industry, irrespective of whether data exchange is done in the form of traditional documents such as drawings and written specifications (as in current practice) or in the form of models intended directly for use in computer applications (as expected in future practice). Bindslev (1995) discusses logical structures of classification systems.

Many countries have national classification systems for building elements, work sections and construction products. Many of these are, relatively similar in their overall structure, although they may differ significantly in their detailed categories and coding principles (Laitinen, 1998).

As discussed in Chapter 3, design involves the activities of searching, analysing, manipulating, structuring information and generating new information. These activities do not form a linear process, but take place in loops. The output of the design is information concerning the definition and specification of selected or generated solutions. Output of design also involves combining new information with that which already exists in the design, finding new relations between known data and developing or discovering new structures in concepts and ideas that lead to design solutions. This means that information is treated as static data, although its content and structure are invariably subject to change. Thus, an information model for providing information related to the assembly of building components during the construction process requires a flexibility that allows for re-definition and restructuring of information during the information exchange between designers and site teams.

5.1.2 Buildability Information Framework

The literature review and industry survey presented in this thesis addressed the requirements that must be met by the way graphical design information are defined and communicated and what type of information has to be dealt with. This chapter develops a framework for design information communication during the construction stage of a project that fulfils these requirements and can form the basis for the design and development of design support systems that incorporate buildability graphical information flow. Hence the framework is called Buildability Information Framework (BIF)(Figure 5-1).

The main issue in the development of such a framework is that the information flow model that results from working with this framework should meet the requirements of the visualisation system for communicating the buildability related information that were formulated in previous chapters.

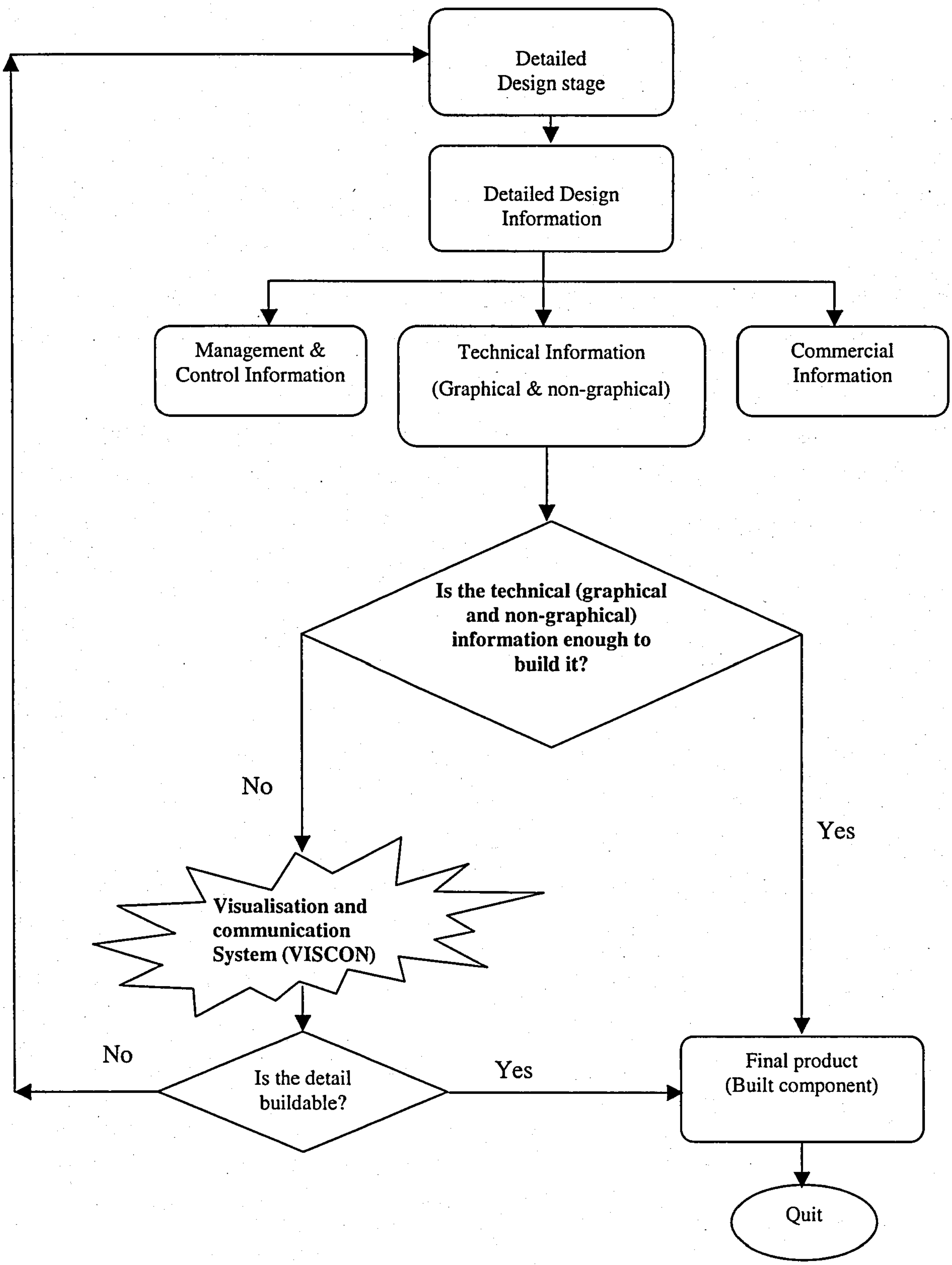


Figure: 5-1 Buildability Information Flow Framework

The graphical information flow works as a diagnosis module. The diagnosis module analyses a given design, detects buildability problems, and reports them to the site team. It checks the possible problem the site team may face in assembling, and interfaces between different building components. The diagnosis begins with the extraction of a list of the common problem areas (cladding, roof, etc.). The design team checks if the contractor possesses the skills and experience to carry out that specific detail without facing any difficulty. It also checks if a specific design detail is clear enough, and 2D drawings are sufficient for communicating the design intents, decisions and problems. If it is not so, then the design team have to use the VISCON system to analyse and present that specific design detail. As can be seen in Figure 5-1 the design team may pass the design details assuming that it is clear enough and can be understood, but the site team cannot understand the design intent, decisions and problems and face difficulties in implementing that part of design. In this case the site team have to contact the design team and use the VISCON system. As the industry survey (postal and case study interviews survey) showed that buildability problems are not similar and differ from one building to anther, the framework has been developed to be generic and not specific to certain building components (e.g. roof, cladding, etc).

5.2 WHY THE VISCON SYSTEM IS NEEDED

As discussed in Chapter Three and the analysis of the survey, traditional tools are not adequate to communicate design intent, decisions and problems properly. In addition, communicating information through paper-based graphical representation limits the design and construction teams' ability to work together to solve problems arise during the construction stage of a building. Moreover, paper-based communication does not provide the interaction needed to focus a project team's attention on the most relevant information. Visualisation-based communication approaches can be more powerful than paper-based communication approaches because they support the participants in co-ordinating the work and related information on projects by making interaction more effective. This was confirmed by the industry survey and case study interviews undertaken at the early stages of this research project, this showed that:

- Traditional visualisation and communication tools have certain limitations for the exchange of design information between design and site teams;

- Many buildability problems are caused by the lack of clear and sufficient information to assemble certain building components, or by misunderstanding that information;

- Design details intent, and decisions were not always understood by the site team because these details were not adequately presented;

- The industry survey showed that the use of computer visualisation was limited to the conceptual stage and mainly to present designs to clients to obtain their approval;

- There is a necessity for site visits by the design team to investigate problems that arise during construction, these site visits are time and money consuming;

- The collaboration between design and site teams was ad hoc and not properly organised i.e. there was no conceptual framework for collaboration and communication between the two teams during the design and construction process;

Although there is a need for adopting computer visualisation as a communication tool for the exchange of design information related to buildability problems at the construction stage of a facility, current research efforts do not address the issue of the industry needs that computer visualisation can fulfil. The development of a system architecture, for the use of computer visualisation to communicate design information, is, therefore, essential for improving communication/collaboration in the construction industry.

5.3 SYSTEM REQUIREMENTS

The literature review and industry survey identified the requirements for a system that can facilitate the communication of detailed design information. The requirement analysis has identified a set of features that will be desirable to the future users. The system should:

1. be based on widely used PC hardware in the construction industry;

2. support standard protocols for 3D modelling, rendering, animation creation, visual, audio and data communication, and a range of a common network architecture;

3. use existing software, wherever possible, available at low cost or free of charge;

4. facilitate data exchange and transfer;

5. allow the users to share a whiteboard or other software available in one PC and not available in others;

6. provide tools for data management or on line record keeping;

7. provide and maintain physical contact (eye contact) similar to that available in face to face contact;

8. allow for asynchronous and synchronous collaboration.

5.4 VISCON FRAMEWORK

For this research project the purpose of modelling is to represent the methodology that is being proposed for identifying possible buildability problems that arise during the design and construction stages as a result of improper information communication, and how computer visualisation and communication tools can be used to solve these problems. As this methodology involves the integration of various tools and techniques for information communication to solve buildability problems, an adequate representation of the process and information for communicating design details that may cause problems during construction is required. This could be achieved through the use of existing modelling methodologies, which deal with process and information modelling and which satisfy the requirements for modelling information communication using computer visualisation and communication tools.

The conceptual model (Figure 5-2) for the proposed Visualisation Support for Buildability (VISCON) system was developed based on a set of criteria which can include: the ability to adequately represent the intended functions and interrelationships, ease of use and understanding, applicability within the construction industry, the ability to represent different perspectives (e.g. information communication and exchange, collaboration) of the system.

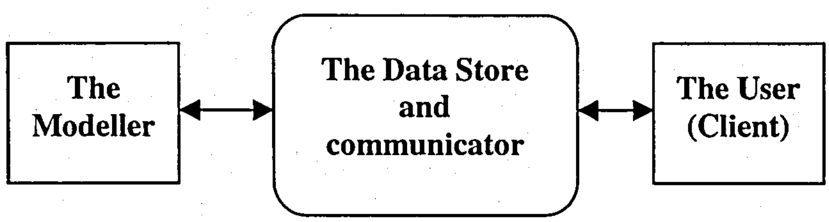


Figure 5-2 VISCON Architecture

As shown in Figure 5-2, the VISCON system is composed of three major parts: modeller; data store and communicator (server); and user. The server can be run on one of the Web-based ASPs, the designer's computer or the contractor's computer.

The following sections describe the system components:

The Modeller

The modeller component is responsible for mapping the data into a view model, which is an abstract representation of the scene to be rendered. This process is usually carried out in design team PCs. In the modeller, the design team generate the required visualisation for the part that needs to be clarified. 3D models will be created using the information available. The 3D model created can then be used as the basis for any type of visualisation required.

The Data Store and Communicator (the Server)

The data store and communicator (the server) can be either on the design team server, or wherever the Internet is available with sufficient space on server. It links the user or the client PC to the modeller PC. The server works as the store for data input by the design and site teams. The design team information can be either graphical or textual depending on what the team considers necessary for constructing a specific component in addition to the standard information provided. In addition to this information, the design team should input the reply to the site team's requests. The server should be set up by the design team. The site team members can access the server via the Web. This allows them to get the necessary information, or submit their input, which can be either requests for information, or query. They can also input information that can help the design team to solve a specific problem. Design and construction teams can use the communicator to set up time for meetings which can be either using the system or any other type of traditional meetings.

The proposed system is linked to a communication system which consists of Microsoft NetMeeting, an Internet-based video communication tool that provides many features, such as video conferencing, real-time whiteboard collaboration, real-time chatting, file sharing, and file transfer during a NetMeeting Conference.

The User (Client)

The users of the system are the site team members. The system is developed assuming that there are PCs on the construction site with links to the Internet or Intranet. The PC should run DWF Viewer or any other Web format that can view CAD drawings, Cosmoplayer or any other VRML browser to view VRML models, Media player or any other animation player to view 3D animations, and DWG Viewer to view CAD drawings.

5.5 ASSUMPTIONS IN DEVELOPING THE SYSTEM

In the development of the VISCON system, it was assumed that:

1. There is a design coordinator on site who is in charge of supervising the design implementation. This person is usually the project manager or an engineer appointed by the designer to help the site team in understanding the design information. This design coordinator should be computer literate so he/she can view the visualisation models, and use the communication and collaboration tools.

2. There is a design coordinator in the architect's office who should be computer literate, with access to a visualisation and communication developer so that they can produce or coordinate the production of any visualisation required on site. This design coordinator can be the design manager if he/ she possesses adequate experience.

3. The hardware and software required to run the system are available on construction sites and design offices.

The overall architecture of the proposed system for computer visualisation and communication for exchanging design information related to buildability problems is presented in the next section.

5.6 THE VISCON ARCHITECTURE

A "visualisation system" is an interactive system for presenting part of a data space in such a way that a user with some purpose in mind can visualise the data for that purpose (Taylor 2001). This definition of a visualisation system contains several important terms, each of which must affect any guidelines for evaluating the system. Most importantly, it is the user who does the visualising. A visualisation system is not a system for making a picture out of some attributes of the data. Indeed, data presentation need not be wholly, or even partially, visual, provided that it allows the user to visualise --to make a mental picture of--how the data fits the purpose.

The VISCON system architecture designed using visualisation applications to clarify and communicate buildability information is shown in Figure 5-3. The framework can be assumed to be a closed loop of interaction between the designers, the VISCON system and the site team. As it has been mentioned in Chapter 1, the scope of the research is to develop a prototype system for clarifying and communicating graphical helps the design team to choose which type of visualisation is appropriate for which part of the building with potential difficulties on site.

The visualisation system consists of three main levels. The data flow, which is represented by an arrow, depicts the fact that data moves from one process to another. The levels represented in Figure 5-3, transform data either by changing its form and adding to it or by generating new information from the data. A process must have at least one data flow coming into it and at least one leaving it, except from two components: where the incoming data flow comes from or where it ends; the first is a data generator and the second is where data is stored or used to get the final product. buildability information. The system architecture described shows when the system is needed for clarifying design details using 3D visualisation. The system architecture described helps the design team to choose which type of visualisation is appropriate for which part of the building with potential difficulties on site.

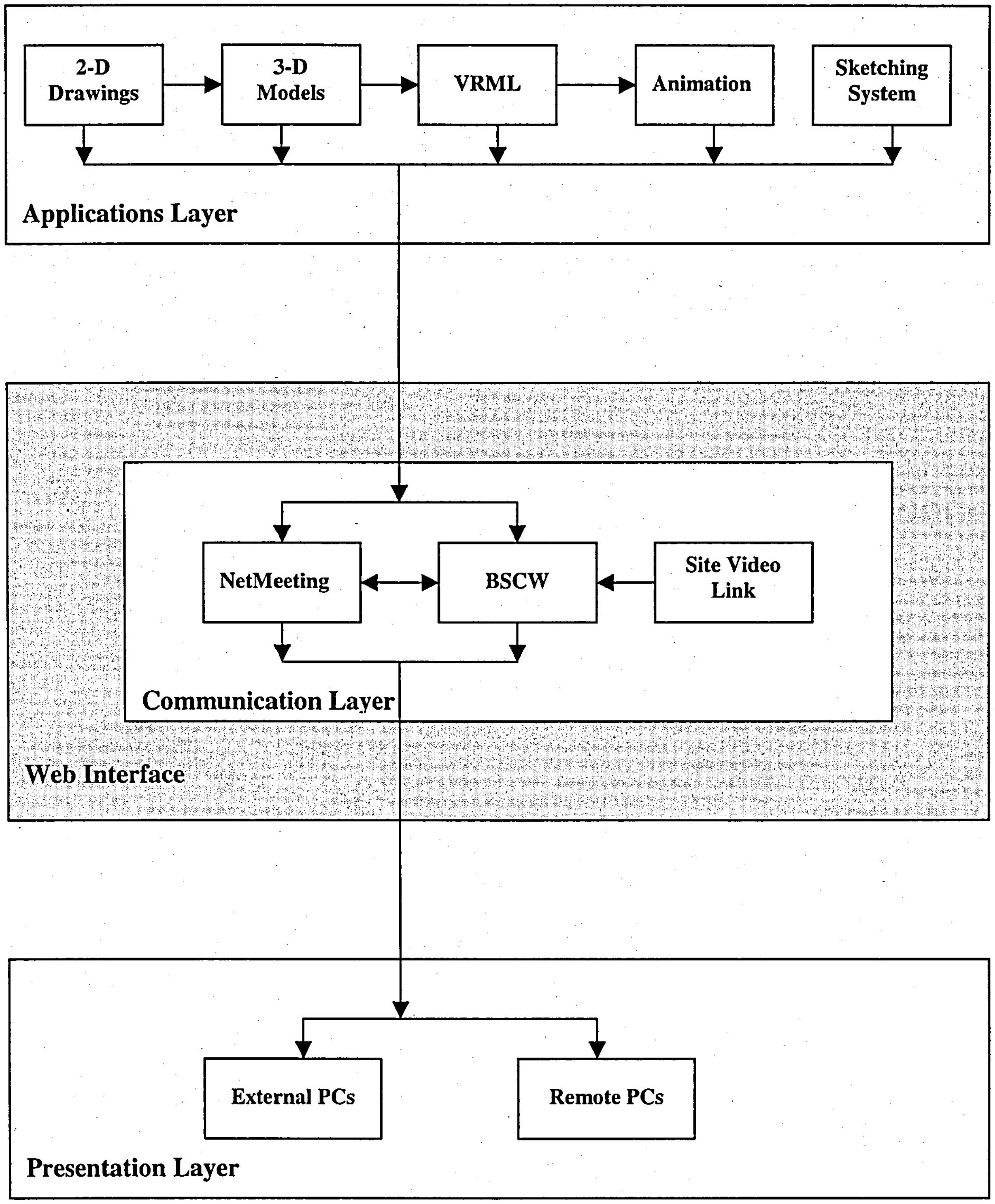


Figure 5-3: VISCON System Architecture

The first level of the visualisation system is where the 3-D models are created from the 2-D drawings and textual information using one of 3D CAD modelling tools. These models are the basis for the visualisation system. Creating 3-D models is not as easy to produce as 2-D drawings or physical models. When creating 3-D models, each method has its own characteristic advantages and disadvantages. It is necessary to identify at the outset the best method for creating a 3-D model for a specific component of a building or for the whole building. Each 3-D object can be created using one or more 3-D modelling techniques such as solid modelling techniques, or wire frame techniques.

Another method of creating 3-D models is the 3-D sketching tool. Sketching is a powerful means of communication between people, and while many useful programs have been created, current systems are far from achieving the same results as freehand sketching.

Having the 3-D model created and ready for use, it can then be transferred to the rendering system. At this level, materials can be added to the 3-D model to give it a 'real' appearance. 3-D animation can also be set up and created during this stage.

During the third level, the outcome from the second level of the system is decided. It can be a VRML model, 3-D animation, rendered image or any other visualisation. The decision on what type of visualisation should be produced depends on the information that should be presented. It also depends on the particular project and its constraints as well as on the way of working. If the visualisation aim is, for example, to show how components can be assembled, the best visualisation system to use 3-D animation. To view the final product, it is best to use the VRML model, which can be manipulated and viewed from different angles and sides.

Rendered images can be useful to visualise materials and their appearance. This enables users to decide on the best materials from an aesthetic point of view. The system also offers other visualisation systems currently available (such as VR) and is flexible to be able to incorporate other systems that will be available in future.

All visualisations and information on the design of a specific part of a project are created within the system and linked to the main drawing. 3-D animations, VRML, rendered images etc., can be hyperlinked to a 2-D plan of the proposed building or structure using hyperlinks so that it can be downloaded from the Internet. This allows the viewing for the visualisation and information produced for a specific component. Site video link can also be set up by having a web camera on the construction site and linking it to the Internet or Intranet.

The type of image for presentation should be chosen in each case according to features required. Table 5-1 describes each type of image and its possible use.

Table 5.1 Computer Visualisation Features

	Details	Features	Purpose
Rendered images (still images)	Images using fixed viewpoints.	Skilled presentation of viewpoints, perspective representations, etc., are needed to create 3-D images.	Promote understanding of the entire project; compare proposals with current situation; compare different proposals.
Animation	Image presentation by certain viewpoint transfer	Makes it easier to conceive of 3-D images; can be presented only according to case study; allows simulation of continuously changing viewpoint.	Simulate an operation to understand how to assemble certain building components
VRML	Image presentation by certain viewpoints	Although the viewpoint is fixed, the viewpoint can be changed continuously, in an interactive manner.	Checking the designed building (the entire building or one of its components).
Walk-through	Image presentation by viewpoint transfer at the user's discretion.	High-function hardware is required for production on the system	build understanding of an entire project

5.7 COMMUNICATION AND COLLABORATION USING VISCON

Communication is the process by which information is exchanged between two or more people. In most cases, this involves identifiable participants, but it also includes information exchange between organisations. This information must be captured and represented in order for it to be analysed and processed for the benefit of an organisation or a project (Rezgui & Bouchlghem, 2001). The process should ensure that information is captured effectively. Poor, late or inaccurate exchange of information often results in mistakes, which when rectified at the construction phase result in excessive costs (Kagioglou et al, 1998). The complexity of large construction projects, specialisation of the project participants, and different forms of synchronous and asynchronous collaborative work increased the need for intensive information exchange (Fruchter, 1996).

To enable efficient collaboration, the process needs to be supported by electronic means, especially if it takes place between dispersed groups. These electronic collaboration tools need to support the usual work. In particular, they need to provide:

- a rich variety of tools for asynchronous and synchronous collaboration;
- a smooth transition between asynchronous and synchronous modes of collaboration,
- a close integration into the normal working environments of the users, and
- cross-platform interoperability since, in general, multi-disciplinary teams use a variety of platforms.

In order to choose the most suitable tool to support collaboration function of the VISCON system, a comparison between a number of communication tools available that can be used for collaboration has been conducted. The comparison criteria used were the characteristics of the tools in term of data format and records. These are shown in Table 5-2, which leads to conclude that BSCW is the most suitable tool for collaboration, and can be integrated with the proposed system (VISCON).

Table 5-2 Comparison of communication tools

	Data format	Records	Comments
E-mail	Text, image,	User's machine	Records in participation time
BSCW	Text, image, movie, VRML	BSCW server	Records all history of project, whenever user references the history, categorised by questions
Chat	Text	Not saved or user's machine news server	Records in participation time.
Newsgroup	Text	News server	Records in participation time

The prototype system adopted the BSCW (Basic Support for Cooperative Work) system as it fulfills the above requirements. BSCW is a Web-based groupware system for asynchronous and synchronous co-operation developed at GMD (German National Research Centre for Information Technology). The system was developed to transform the Web from a primarily passive information repository to an active co-operation medium. The BSCW system is an application which extends the browsing and information download features of the Web with more sophisticated features for document upload, version management, member and group administration and more, to provide a set of features for more collaborative information sharing using standard Web browsers.

The central metaphor of BSCW system is the shared workspace. BSCW server (Web server with BSCW extension) manages a number of shared workspaces, i.e., repositories for shared information, accessible to members of a group who have user names and passwords. Shared work space can contain various kinds of information such as documents, URL links to other Web pages, threaded discussions, and member contact information. The content of each workspace is represented as an information object arranged in a folder.

With BSCW, participants in one project can communicate and record problems, questions and answers with multimedia data including text, images, VRML models and animations. The user can then post a message with an attached file, such as an image, VRML or animation.

5.8 SUMMARY

This chapter discussed the conceptual model and function of the proposed VISCON system and its underlying assumptions. The buildability graphical information flow framework has been described. The reasons behind the development of the system and the requirements of the system were also discussed. The limitations of the model will be discussed in the Evaluation Chapter. The implementation of the proposed system for design information visualisation and communication to support site level operations is described in the next chapter.

Chapter Six
Prototype System Implementation

CHAPTER SIX

6 PROTOTYPE SYSTEM DEMONSTRATOR

6.1 INTRODUCTION

This chapter describes a system demonstrator for information visualisation, communication and collaboration during the construction stage of a building project (VISCON). It includes the aim and objectives of the system demonstrator, the scope development environment, and the key features as well as the approach adopted in creating the visualisation and communication environment. Three case studies are presented to demonstrate the prototype system in a computer-based environment.

6.2 SYSTEM DEMONSTRATOR

6.2.1 Aim and objectives of the system demonstrator

The prototype system has been designed to facilitate the communication of buildability information. The main aim of the proposed system was to create a fully integrated visualisation and communication environment that could be easily used by designers and builders even when they are geographically distributed. The development of VISCON reflects the need to realise the benefits of computer visualisation and communication tools. In order to achieve the above aim the following objectives had to be met:

- To develop a web based virtual environment system capable of using different visualisation and communication tools to support the communication of buildability information and fulfil a number of requirements (described in Section 5.4) emanating from observed shortcomings in existing systems used in the construction industry.

- To demonstrate how VISCON can help understand how building interfaces between components and their assemblies.

- to identify any technical problems with the proposed system (VISCON) and make the necessary improvements to it.

- To implement and develop the system using the buildability information flow framework (Section 5.1.2).

In addition to the above objectives of VISCON, the prototype developed was intended to accommodate system attributes which:

1. are practical and easy to use by construction industry practitioners, with reliable and consistent outcome.

2. provide an environment for design and construction teams to collaborate during the construction stage of a facility.

3. use different visualisation techniques each for a specific purpose e.g. using animation to show assembles of building components and VRML models to show interfaces between different building components.

4. using hardware and software similar to those used by construction industry practitioners in order to make the proposed system (VISCON) easy to implement in the construction industry.

6.2.2 Scope of the VISCON prototype

The scope of the VISCON system prototype is to model graphical information related to buildability used by both designers and contractors. The prototype has been developed by integrating a number of existing tools used for information visualisation and communication so as to provide help in understanding how building components can be assembled together correctly and quickly. It is also meant to help users understand how different building components interface.

6.2.3 Development Environment

The system aimed for had to provide an easy and effective way of creating virtual models which represent part of a building and simulates an assembly process of specific components. The tools selected for development were intended to fulfil the construction industry requirements and facilitate use and implementation. Details of the hardware and software tools and the reasons for their choice are presented in the following section.

6.2.3.1 Software Used

The choice of using the MS Window environment for the demonstration was due to the need to quickly develop the system at minimal expense, utilising readily available application packages, which was a major factor in the software selection process, and in line with the resources constraints of the research. The system should be acceptable to construction industry practitioners who are usually reluctant to invest in new software, the other major factor therefore is the use of software packages similar to those widely used in the construction industry.

It was necessary to understand what CAD software can provide in terms of 3-D modelling, which is the basis for most computer visualisations. The software types for the VISCON system consist of three main components, software for the creation of the 3D models, optimised display of the 3D models, and communication tools between the system users. For the creation of 3D models, industry standard software were used, these are AutoCAD 14 & 3D Studio Viz.

Cosmo Player, a browser plug-in software is used to view the VRML models in both Internet explorer and Netscape browsers, other viewers used were: WHIP to view DWF (Drawing Web Format) files, and a DWG Viewer to view AutoCAD files. Finally Media player was used to view 3D animations.

For communication, NetMeeting multipoint Data Conferencing software was used to facilitate synchronous communication. NetMeeting's comprehensive suite of data conferencing tools allow a participant to collaborate and share information with two or more participants in real-time. He/ She can share information from one or more applications on his/her computer, exchange graphics or draw diagrams with the electronic whiteboard, send messages or record meeting notes, action items with the text-based chat program, and send files to other meeting participants using the binary file transfer capability. With a sound card, microphone, and speakers, NetMeeting lets participants talk to associates over the Internet or corporate intranet in real-time. With a video capture card and video camera, they can send and receive video images over the Internet or corporate intranet for face-to-face communication during a meeting. NetMeeting allows participants to receive video even if they do not have cameras connected to their computers. They can also use the video conferencing capability to take a snapshot with their video cameras and place the image on the whiteboard for discussion or mark up.

For asynchronous collaboration, the BSCW (Basic Support for Cooperative Work) software was used. BSCW is a 'shared workspace' system which supports document upload, event notification, group management and much more. To access a workspace, only a standard Web browser is needed. The software vendor maintains a public server at FIT free of charge (Fraunhofer Institute for Applied Information Technology) where the system is available. If anyone wants to run his/her own BSCW server, he/she can install the server software at cost (works on most Unix systems, Windows NT) (http://bscw.gmd.de).

6.2.3.2 Hardware Used

As this research aimed for the development of a visualisation system that can be used by construction industry practitioners taking in consideration the minimum requirements for the above mentioned software, it was decided to use standard hardware found in the industry today rather than a highly specialised graphics workstations. Therefore the PC used was a Pentium II with128RAM and 300Mhz, a

8Mb VRAM/32Mb, a DRAM Diamond Fire GL 3000 graphics card connected to the Internet, a sound card, and a web camera. The display equipment can be either a laptop or desktop type PC linked to a LAN or a WAN to make distributed data conferencing processing and file sharing possible.

6.2.4 VISCON Case Studies

This section presents practical experiments conducted to test the proposed system VISCON. Three case studies were used from real projects. These case studies were: a paper factory, a bay barrage building and a swimming pool. The case studies focused on buildability problems with claddings, roofs and stairs assembling as the survey revealed that these problems were widely experienced by industry practitioners. In the development of the case studies, 3D models were created for some components that may inherently be difficult to assemble using AutoCAD14. These models were exported to 3D Studio Viz for final editing. They may also be exported to VRML at this stage, but this requires additional editing work within one of the VRML builder packages. The editing process in 3D Studio Viz is as follows:

1. Import the AutoCAD 3D model making sure that the settings convert each entity from AutoCAD to a separate entity in 3D Studio Viz assigning realistic materials to each component to give the 3D model a realistic image.

2. Use the Track view window in 3D Studio Viz to add visibility track to every entity.

3. Set the visibility of each entity to correspond to a scaled sequence of its construction

4. Render the animation.

With 3D Studio Viz, the camera can be moved during the course of the animation to focus on particular elements being constructed. For example, while an exterior view is advantageous for illustrating the construction of the cladding, once the sheeting has been applied, the interior structure is hidden. With 3D Studio Viz it is easy to group multiple elements and manipulate them as a group. It is also possible to illustrate the movement of constructed elements, to show for example how an unconventional staircase is assembled. In addition, 3D Studio Viz images and animations provide high quality imagery with ray trace shadowing and multiple light sources, which gives a good sense of three dimensional space. VRML models are simpler in terms of textures and lighting but offer real-time movement and an authentic sense of presence.

6.2.4.1 Case study 1 (Paper Factory)

The first case study was set up using 2D drawings for a factory buidling. The drawings were the plan, the sections and the elevations for the factory. A 3D model was created using the information available on the drawings. The 3D model was then transferred to 3D Studio to create 3D animations and VRML worlds. The 3D animations were done for the staircase to see if there was any missing or misleading information on the drawings (see Figure 6-1). A VRML visualisation was created for

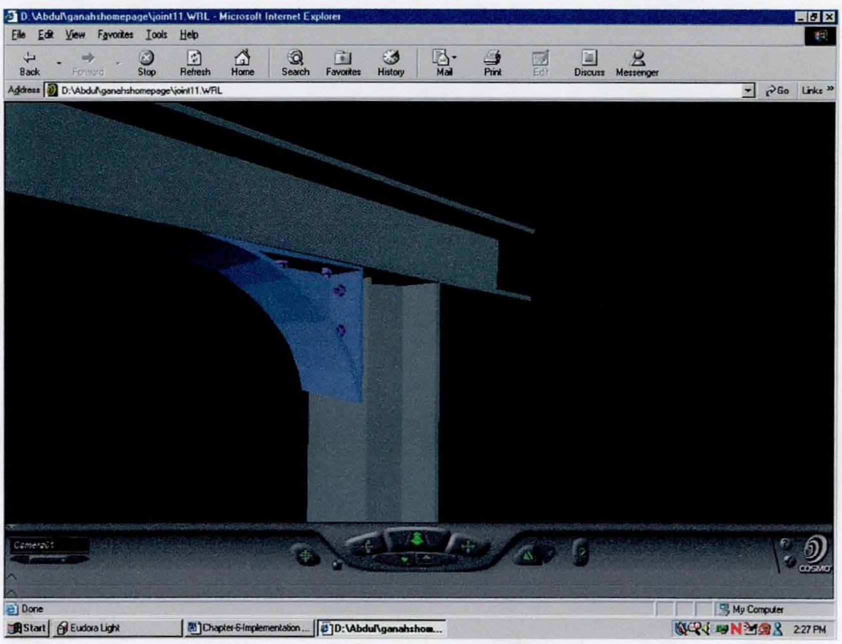


Figure 6-1: VRML Model of Column/Beam Joint

a steel column to show the connections between the column and the beam (see Figure 6-2).

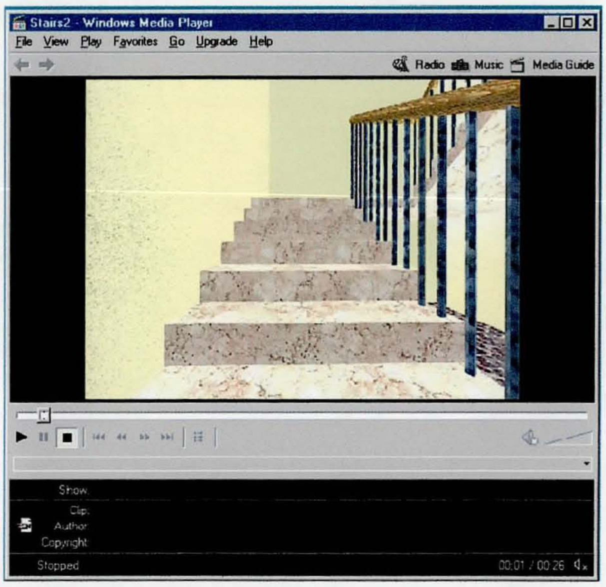


Figure 6-2: Walkthrough animation for the staircase

The 2D plan of the factory was used to provide links (Figure 6-3) to the VRML models, 3D animations and any other information such as the 3D CAD model for the

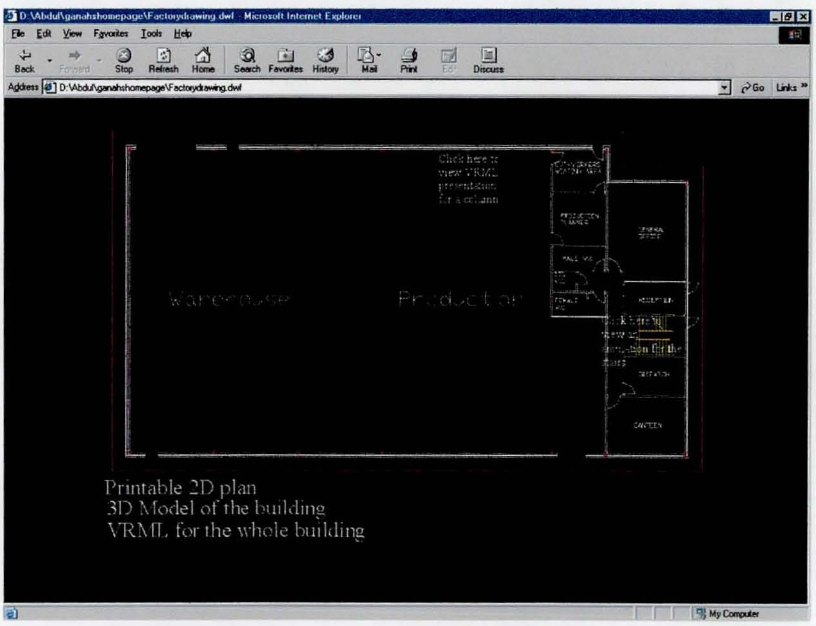


Figure 6-3: 2D plan for the factory with hyperlinks to VRM, 3D animations and 3DCAD Model

whole building. This plan was saved as DWF (Drawing Web Format) so that it can be put on the Internet or Intranet and viewed from any location with access to the Web.

6.2.4.2 Case study 2 (Bay Barrage)

This case study was more complex than the first one, it was developed using a set of working details for a control building of a bay barrage. This set shows details of some parts of the structure of the building that may cause some problems for the builders. Each 3D model was created for a specific part of the structure. From these 3D models, VRML models and animations (Figures 6-4 to 6-7) were created to show how

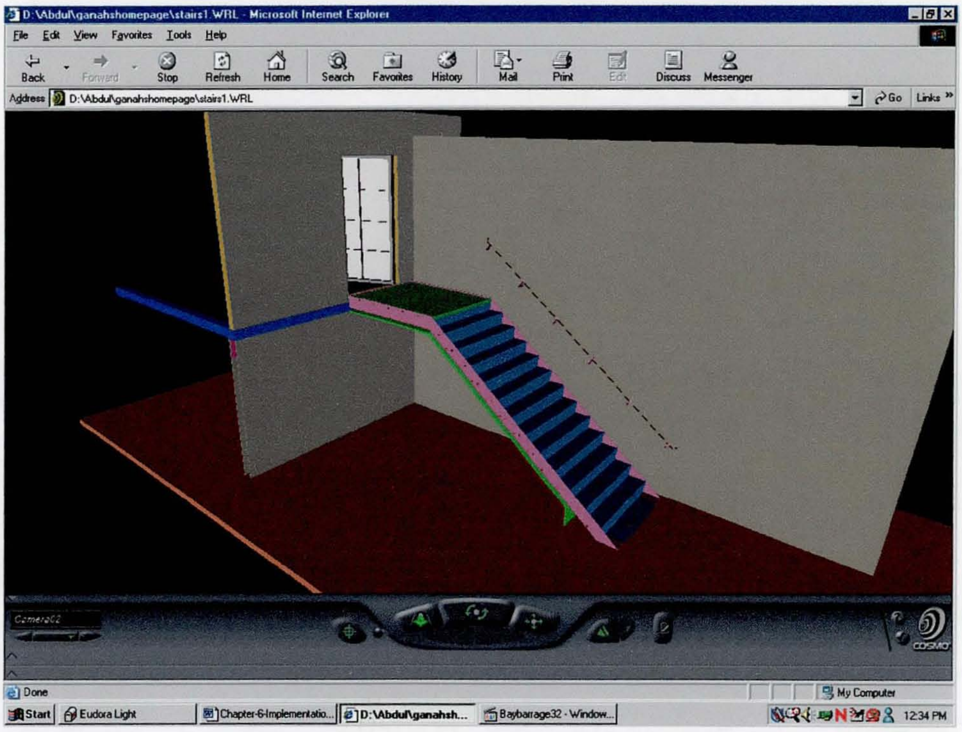


Figure 6-4: VRML model for a staircase

the components of the specific part could be assembled. They also showed how different components interface with each other. As a 2D plan for the building was not available, an elevation was drawn using a perspective drawing of the building. This elevation drawing was used to create links to VRML models and 3D animations. The 3D models and the elevation were put on a Web site for collaborative viewing (Figure 6-8).

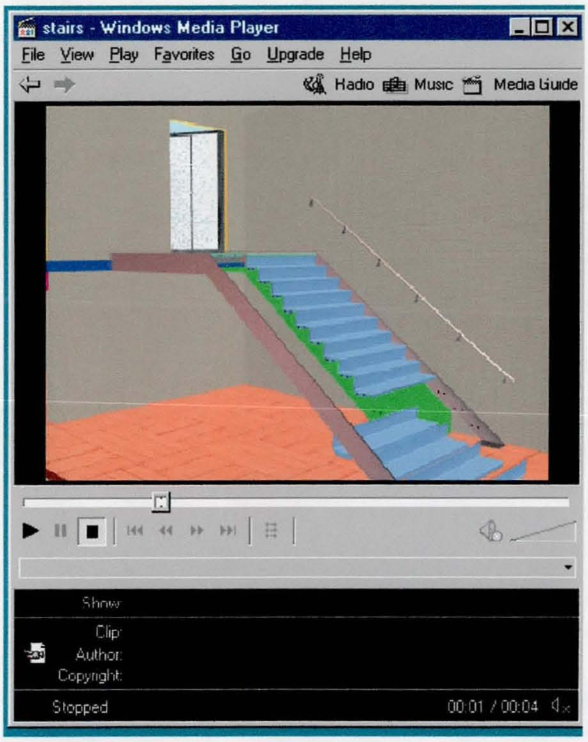


Figure 6-5: 3D animation for a staircase showing how it can be assembled

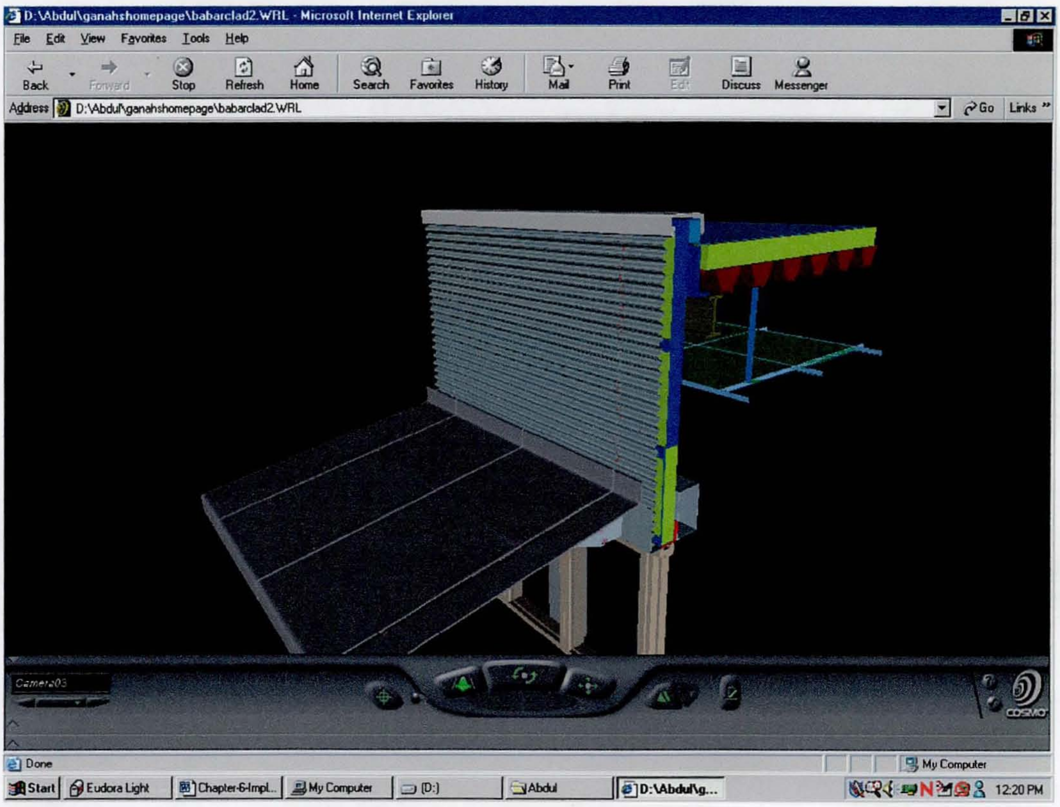


Figure 6-6: VRML model for cladding showing the interface between different building components

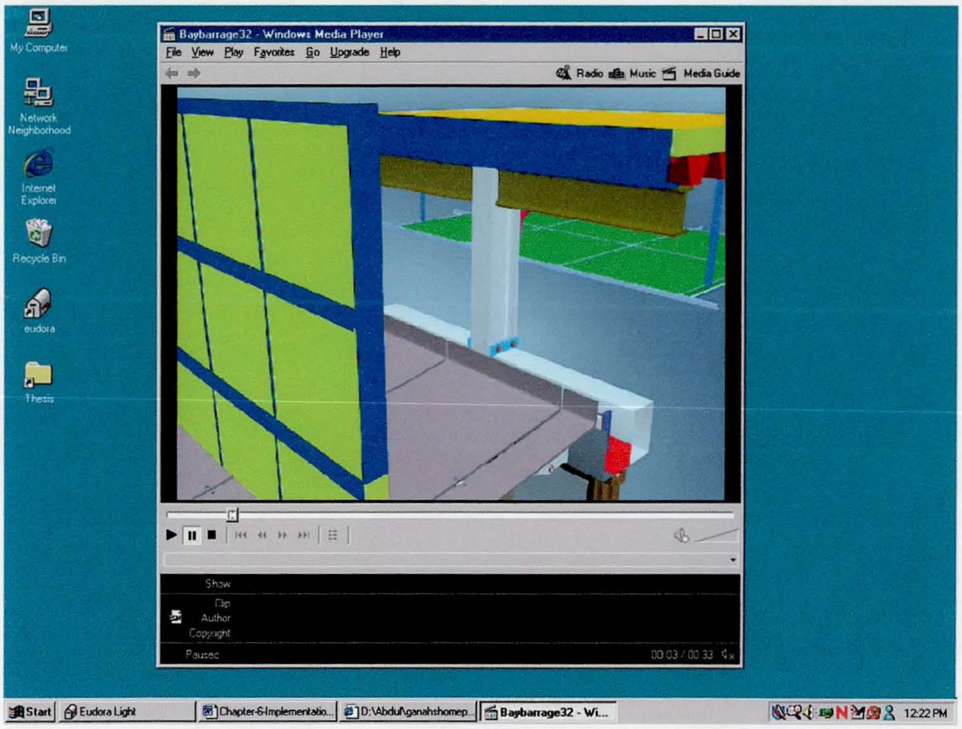


Figure 6-7: 3D animation showing how building components can be assembled

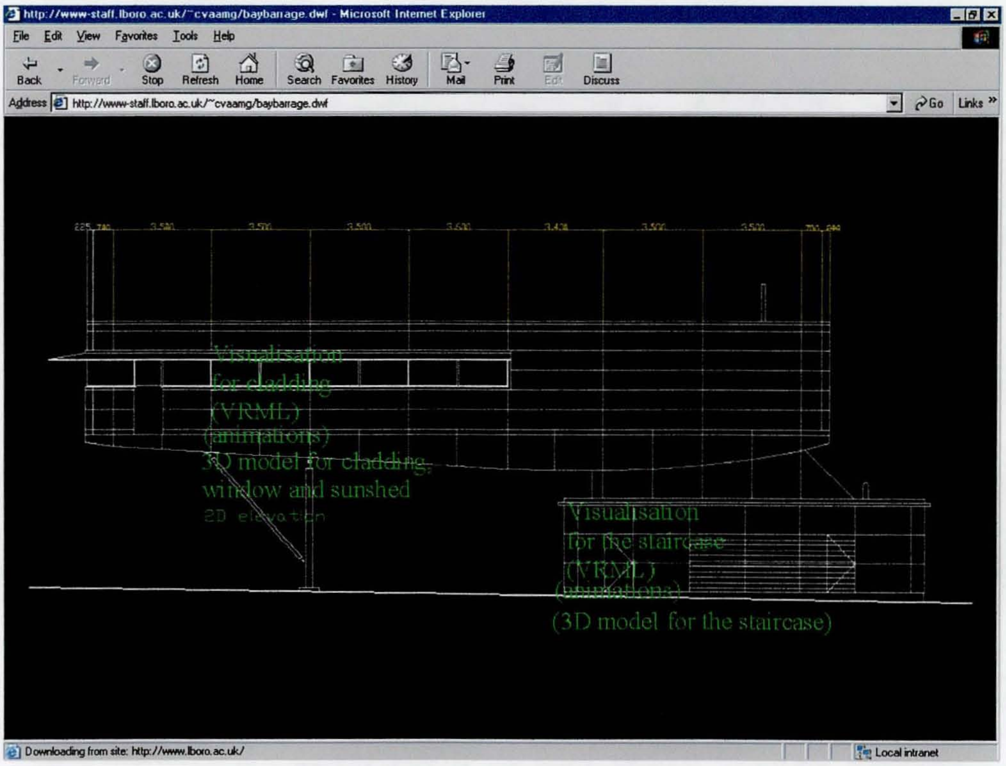


Figure 6-8: 2D elevation drawing for the Bay Barrage Building with hyperlinks to the created visualisations

6.2.4.3 Case study 3 (Swimming Pool)

This case study is set up from a number of drawings for a swimming pool constructed at Loughborough University. The development of this case study differs from the previous two in that it has been based on electronic CAD drawings. The case study includes models for three different areas. The first is a VRML model showing the main steel frame (see Figure 6-9). The second is a model showing interface between the roof and the glazing components. The VRML model shows how these components interface (see Figure 6-10). The animations show how some of these components can be assembled (see Figure 6-11). The third model shows interfaces between the roofing components (the insulation layer, the ceiling and the sheeting) and the gutter components. The VRML model shows the interface between these components (see Figure 6-12). The animations show how the gutter and waterproof components can be assembled (see Figure 6-13). The 2D plan of the swimming pool was used to create the links to the VRML models and 3D animations. This plan saved as DWF (Drawing Web Format) so that can be put on the Internet or Intranet (Figure 6-14).

Figure 6-9: VRML model for the structural frame of the swimming pool building

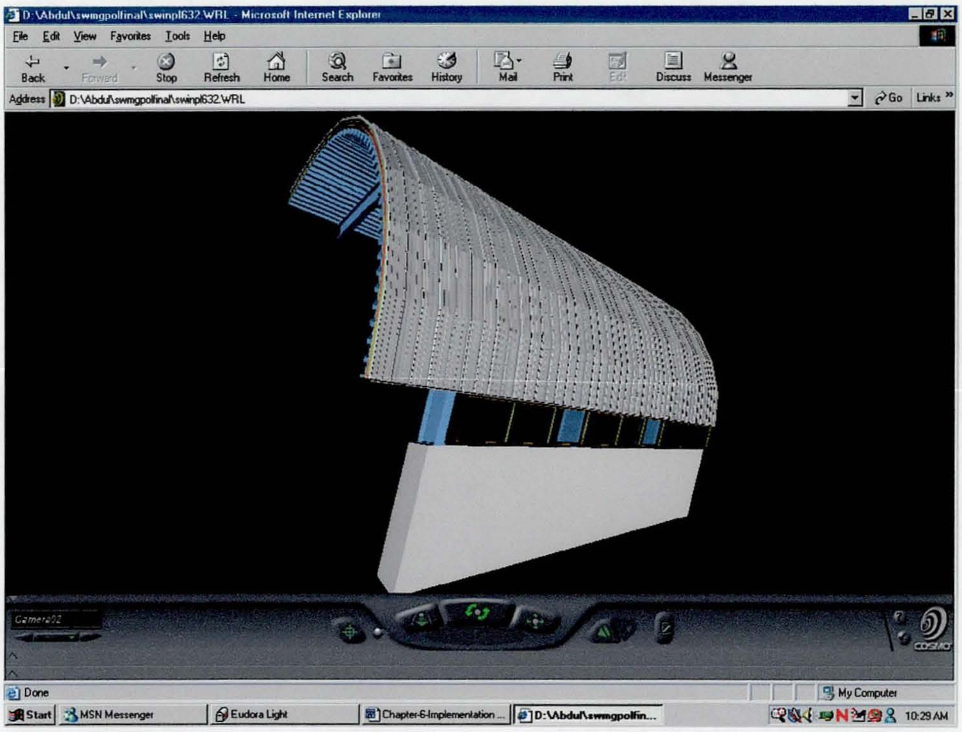


Figure 6-10: VRML model showing how cladding, insulation, glazing and beams interface in the swimming pool building

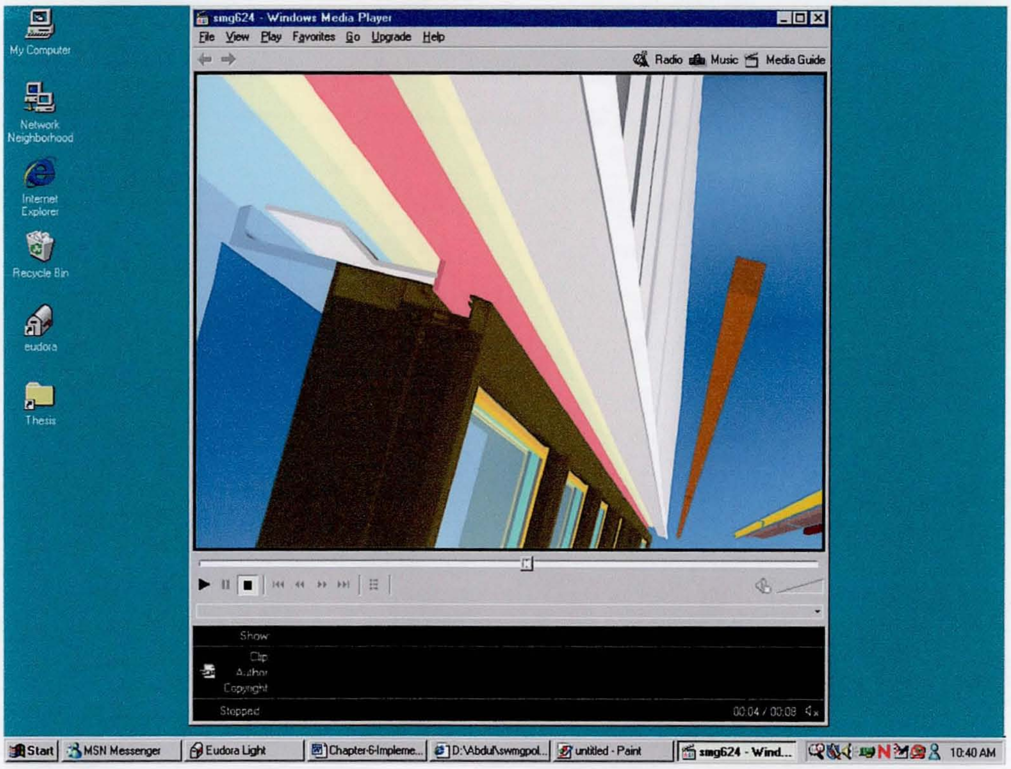


Figure 6-11: 3D animations showing how the insulation layers and other building components can be assembled

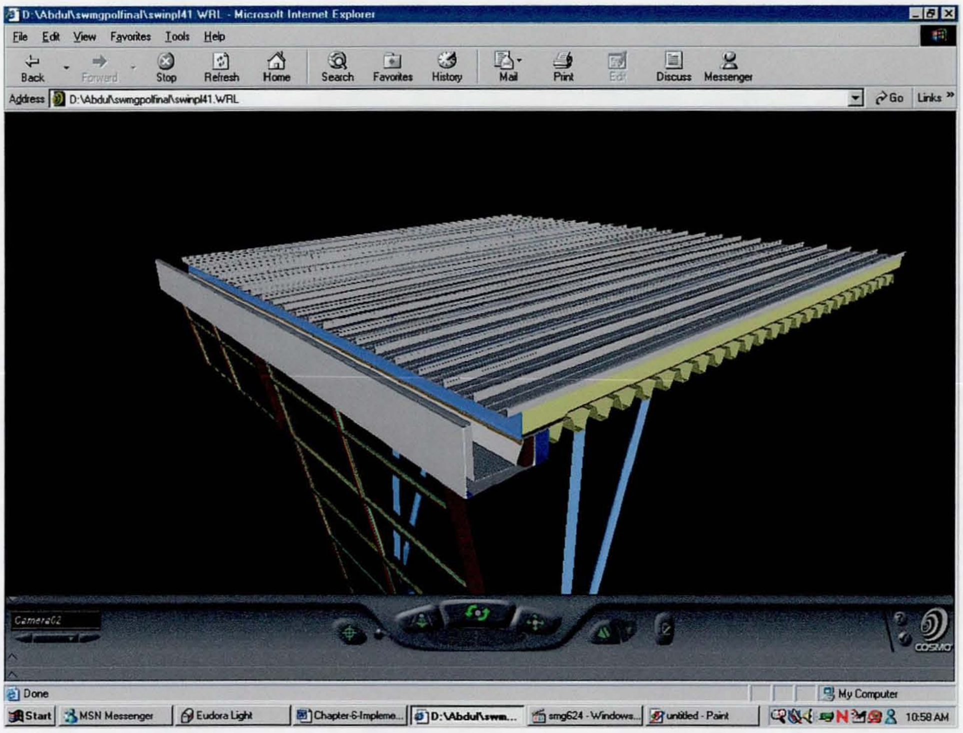


Figure 6-12: VRML model showing gutter, insulation layers, ceiling and roof interfaces in the swimming pool building

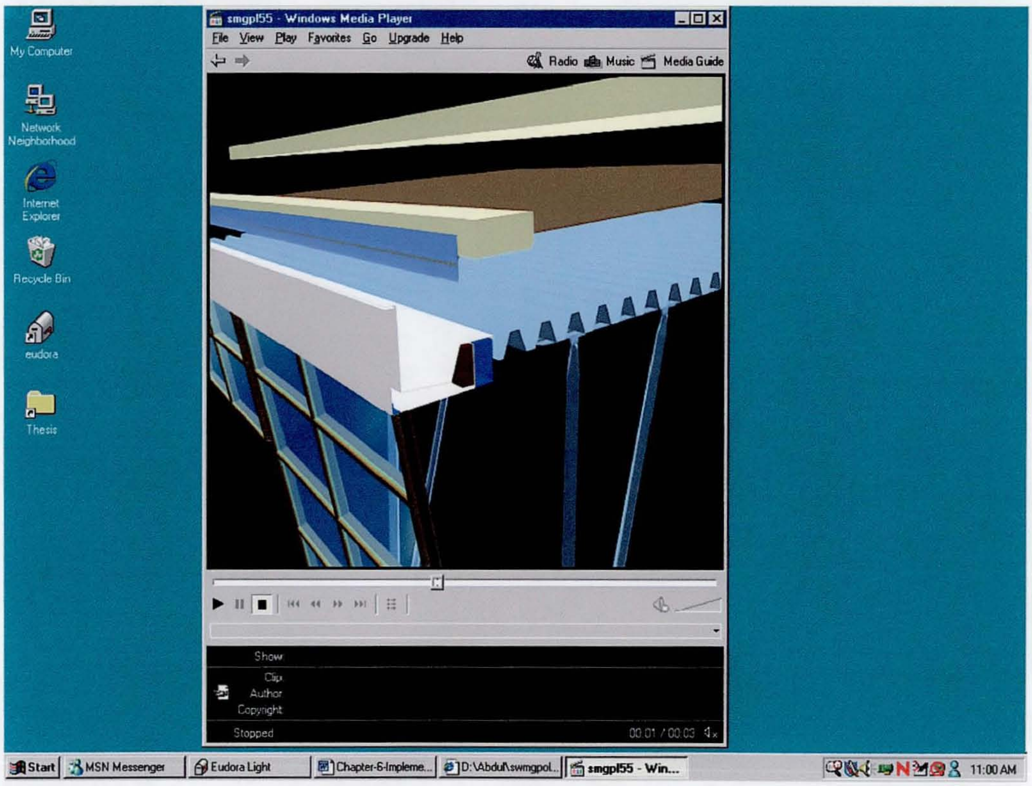


Figure 6-13: 3D animations showing how the gutter, the insulation layers and the roof of the swimming pool components can be assembled

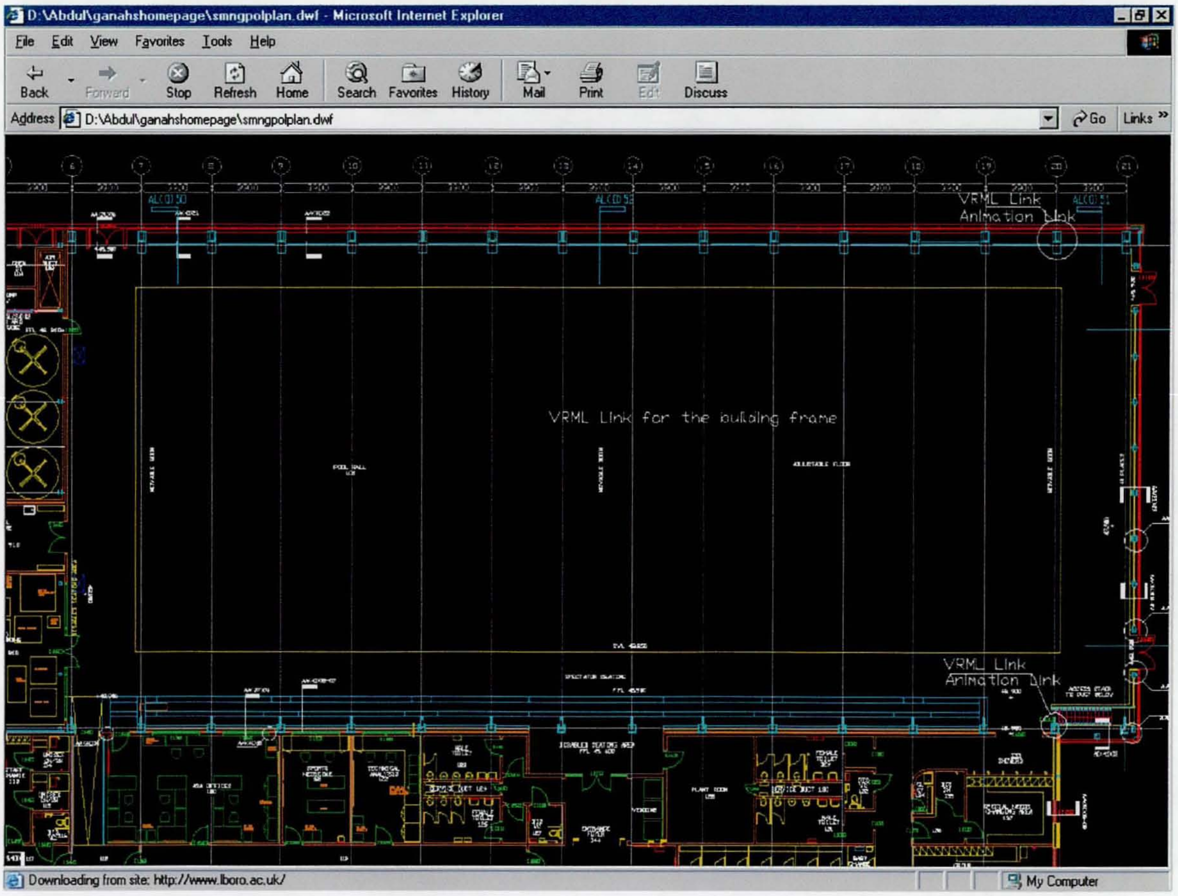


Figure 6-14: 2D plan for the swimming pool with hyperlinks to VRML models and 3D animations

6.2.5 Findings

During the development of the case studies presented above, some interesting findings were captured:

- Building 3-D models can be a lengthy process. There are many different ways of building 3-D models, each method has its own characteristics, advantages and disadvantages. It is necessary to identify at the outset the best method for the task in hand. In addition, each 3-D object can be created using one or more 3-D modelling techniques.

- CAD systems are the source of most graphical data in a project. Many of the commercial CAD systems used by construction firms are primarily geometry modellers and use several file formats (3DS, DXF, OBJ, etc.). The complete data transfer process from CAD to VRML is shown in Figure 6-15. As VRML modelling software do not provide sophisticated modelling techniques used in traditional CAD systems, 3D models therefore need to be created using one of the 3D CAD modelling software. These models can then be transferred to VRML. Translating from the file formats mentioned above to VRML is not accurate and can lead to poor models. The translation is usually a one-way or downstream process (Figure 6-15). The 3D CAD model can be translated into

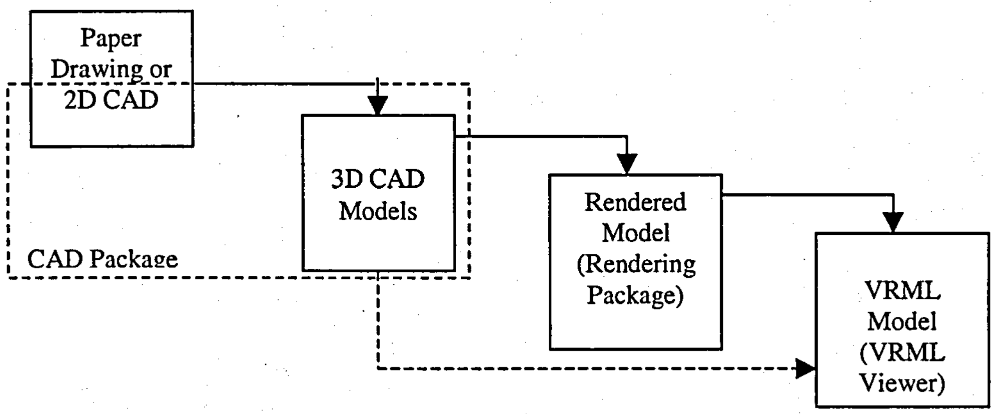


Figure 6-15: Translation of file formats from CAD to VRML

VRML either directly or through an intermediate stage using a rendering package. However, the quality of the VRML model created by direct translation from CAD is of less quality than that created using a rendering package. To facilitate the translation process, the data structure of the 3D CAD model must be re-ordered so that it is acceptable to the destination application, for example a 3D CAD model created in AutoCAD must be exported in a format that can be imported by 3D Studio Viz.

- 3-D modelling helps in identifying any missing information for building a particular component as creating 3D models requires all information to be available.
- The sequence of assembling building components can be easily established.
- By modelling design details, decisions can be made on the design and the results can be seen before the construction starts.
- Building 3-D models for part of a building that contains a buildability problem is much more efficient and less time consuming than creating a 3D model for the whole building especially if the hardware is limited.

6.3 SUMMARY

This chapter described how the VISCON prototype system was implemented and how it operates. Different visualisation and communication tools were used in the development environment. AutoCAD 14 was used as the 3D modelling tool while 3D studio was used as the rendering package that feeds into VRML environment. The Web was used as the communication and collaboration medium. The output was a 2D plan or elevation with links to a VRML models, 3D animations, rendered images, or 3D CAD models. The 2D plan was transferred to a Web compatible format so it can be viewed remotely. BSCW was used as the collaboration tool as it provides a secure store for its users and allows them to carry out all the activities required for collaboration. NetMeeting was used as the conferencing tool to all different participants in a project to meet at any time in their own place of work without the need for travel. The next chapter is concerned with the evaluation of the prototype system.

Chapter Seven
System Evaluation

CHAPTER SEVEN

7 SYSTEM EVALUATION

7.1 INTRODUCTION

This chapter describes the evaluation of the prototype VISCON system, based on two sessions to test its practical application. However, before this is done, the objectives for evaluating VISCON and, the basis on which the evaluation was carried out is explained. This is followed by an analysis of the evaluation results based on questionnaires completed by the evaluators. The benefits and limitations of the system are also discussed.

7.2 EVALUATION OBJECTIVES

In order to reduce the risks associated with implementation of a new computer system, one of the most used methods is to conduct a pilot implementation (Rojas & Songer, 1999). In a pilot implementation the new system is applied to a small part of the process with the objective of correcting technical problems and evaluating the effectiveness of the system in real life settings before large-scale implementation.

The primary interest in evaluating the VISCON system is to identify areas that require improvement. In addition to this, the evaluation had several other objectives that can be summarised as follows:

1. To demonstrate that the prototype has achieved the aim of this study as outlined in Chapter 1;

2. Identify and correct any inconsistencies or aspects of the prototype system that are confusing or misleading;

3. To assess the suitability of the system for its target users;

4. To assess the effectiveness of the proposed system in:

   - solving buildability problems (interfaces between building components and difficulty in assembly) that may arise during construction
   - promoting collaboration between design and construction teams
   - improving the communication process between the design and construction teams.

5. To obtain comments and recommendations to guide future development.

To achieve the above objectives, it was decided that potential end-users of the proposed system needed to see a live demonstration of its use. They would then be requested to complete a questionnaire, which will allow them to express their opinion on various aspects of the system. It was also felt that contractors and consultants who had been interviewed before (those who have been selected for interviews presented in Chapter 4), could be used for the evaluation. However, some constraints prevented the involvement of all those who had been previously involved in the research.

7.3 EVALUATION PLANNING AND CONSTRAINTS

It was decided to invite industry practitioners for a demonstration of the case studies at the university. However the number who attended was very small therefore it was decided to load the demonstration and the presentation on a laptop and visit a number of firms who agreed to participate in the evaluation. Due to work pressures in these firms, the evaluation sessions were carried out during lunch breaks which in some cases did not give adequate time for the evaluators to assess the system adequately. This also made the evaluation stage lengthy and costly.

7.4 EVALUATION APPROACHE

One way complex systems are often evaluated is by looking at isolated elements of the system, using an underlying assumption that if the elements work well, then so will the system. Sometimes this may be a correct assumption, but it is not guaranteed to be correct. Alternatively, systems are sometimes evaluated by how well they perform as an integrated whole in the situation for which they were designed. This is, of course, the ideal situation for evaluation. It is impossible to say how well the system is performing, in relation to how well it might perform with some little change, and the complexity of an environment that requires the use of a visualisation system usually precludes a meaningful variation in the conditions under which the system is tested. For example, the best test of a visualisation system in support of battlefield command and control is whether the user of the system is more often on the winning side than would otherwise be the case; but normally only one such test, if any, is performed, and by the time the results are in, it is too late to do anything about it.

Another problem with whole-system testing is that it is hard to isolate what may make a system effective to use. It is not always the system that appeal to the users that work the best. For example, a well designed system may be completely undermined by allowing a user to choose attractive display colours that make it impossible to distinguish critical differences that a less aesthetic colour scheme would clearly differentiate. These approaches involve testing a system that has been constructed. But it is at least as important to try to evaluate the design of a system, so that it is likely to work well--even if not provably so--when constructed.

7.5 EVALUATION PROCEDURES

Typical evaluations in the area of visualisation systems such as virtual environments has focused on ad hoc user studies, since most of visualisation system applications developed are for specialised areas, for example flight simulator for pilots or application assisting surgeons or fighters in operations. These are usually conducted with a small group of users from the domain (Palamidese, 1999). As the VISCON system is for a specialised audience, a limited number of experts are readily available to evaluate the prototype within the given time, therefore, the following procedures were adopted:

Self-evaluation: tests of the system were performed during the development process focusing on the different components.

Pilot evaluation:- A pilot evaluation was conducted to identify any problems with the system and trial the evaluation questionnaire. It was also aimed at making any final refinements to the system in response to any suggestions or comments made by the evaluators. As it was not possible to involve people from industry in the pilot evaluation, it was mainly focused on a review by other researchers within the department who had industry experience.

Final evaluation:- This evaluation was carried out during the final stages of the system implementation and involved two groups; the first group consisted of 11 researchers and the second group consisted of 18 practitioners from construction industry. The following sections discuss the methodology and results of the final evaluation.

7.6 QUESTIONNAIRE DESIGN

The questionnaire was designed so that VISCON could be evaluated against the requirements for buildability information communication between design and construction teams. It was developed so that the performance of the system in communicating buildability design information could be assessed, and the system's efficiency and quality of the user-interface evaluated. The questionnaire was divided into three sections;

I. Section A included information about the participant's professional role and experience;

II. Section B contained a total of 21 questions about various aspects of the system; these were grouped into the following sub-headings:

- Buildability information communication,
- applicability to the construction industry,
- management of system;
- efficiency; and
- a general section.

For each question, participants were asked to tick the box that best represents their assessment on a scale of 1 (poor) to 5 (excellent).

III. Section C included comments on ways to improve the system, and other general comments.

The sub-sections of the questionnaire were driven by the aims and objectives of the research focusing the evaluators attention on what is important to the study. Other areas of interest were considered under the general headings, such that contribution from the evaluators would also be assessed against the overall performance of the VSICON prototype. A copy of the evaluation questionnaire is included in Appendix D. The results of the evaluation sessions, suggestions, comments and recommendations from the evaluators are presented in the following sections.

7.7 THE EVALUATION

This section contains the details of the two evaluation sessions of VISCON prototypes.

7.7.1 Session 1: Researchers Evaluation

In this session, 11 researchers from the department have been involved. A brief description of the system architecture was given to the evaluators. They were also given brief details on how the VSICON case studies were developed. Then demonstrations of the Bay Barge building and The Swimming Pool building case studies (presented in Chapter Six) were shown. The demonstrations included how VISCON can be used to study the interfaces between different building components and show their assembly sequence. This was followed by a discussion where the evaluators asked questions relating to the system and the research project.

7.7.2 Session2: Evaluation by construction industry professionals

The second evaluation session built on the first one and improved the method used and information supplied to evaluators. Therefore, a brief summary of the aim of the research and the proposed system was given to the evaluators. A demonstration for the VISCON case studies was shown as above. After the demonstration, the evaluators were asked if they wanted any clarifications on the system. The evaluators asked questions about the system. At the end of the evaluation session, the evaluation questionnaire was then given to complete.

7.8 EVALUATION RESULTS

This section discusses feedback from the evaluation participants. It includes the results from each of the two evaluation sessions undertaken. A discussion section gives an overview, detailed results from the questionnaire, and suggestions for improvement.

7.8.1 Overview of Findings

The performance of the system was judged to be highly satisfactory. The rating of the questions in the questionnaire showed that the prototype system can adequately perform the function it was designed for. Some discussion during the evaluations were centred around combining textual information with the models.

7.8.2 Evaluators Background

As it has been mentioned earlier, session1 evaluators were a group of researchers in Civil and Building Engineering Department at Loughborough University. Most of them worked in the construction industry and six of them had more than 10 years experience (see Table 7-1). The evaluators came form either architectural or civil engineering background. Although they currently work in an academic environment, they have been actively involved in industrial practice and have had close connection with practitioners making them fairly representative of the potential users of the VSICON prototype. Therefore, the experience of the participants was considered to be adequate to enable an objective assessment of the system.

Table 7-1: Researchers Specialisation and Experience

Previous position in construction industry	**Experience (Years)**
Construction Manager	25
Building Engineer	3
Design consultant	14
Structural Engineer	10
Civil Engineer	10
Civil Engineer	3
Architect	2
Building Consultant	20
Structural Engineer	4
Civil Engineer	9
Civil & Structural Engineer	2

The group, who participated in the industry practitioners' evaluation session, consisted of a broad range of professionals who worked in the construction industry for several years in deferent positions to including IT experts, structural engineers, architects, civil engineers and researchers in construction management. They represented five firms with an average of 6360 employees, and an average annual turn over of £54.4 m (see Table 7-2). These evaluators were considered suitable as each one had a specific area of expertise that is related to the development of the proposed system under evaluation. Except for the two principal engineers, all the others are directly involved in the daily design activities. Table 7-3 presents the evaluators positions, specialisation and experience.

Table 7-2 Details about industry evaluators' Organisations

Firm	Number of Employees	Annual Turnover
A	26,000	£70m
B	1,800	£85m
C	1,200	£40m
D	300	£17m
E	2,500	£60m
Total	*31800*	£272m
Average	6360	£54.4m

Table 7-3 Industry practitioners Specialisation and Experience

Position	**Area of experience**	**Experience (Years)**	**Position**	**Area of experience**	**Experience (Years)**
IT Associate	Structural Engineering, IT & 3D Modelling	8	Architect	Visualisations (3D)	1
Facade Architect	Architect	13	Design Engineer	Civil & Structural Engineer	5
Façade Engineer	Structural Engineering & Facades	4	Associate Engineer	Civil Engineer	20
Structural	Building	25	Engineer	Building	5
Principal Engineer	Building	19	*Associate Engineer*	Building and Structural Engineer	20
Principal Engineer	Building	15	CAD Technicain	Buildings	30
CAD Co-ordinator	*Building Services, Architecture, Building Surveying*	8	Design Consultant	Electrical Engineer	6
Engineer	Civil Engineering	4	Structural	Civil & Structural	5
Engineer	Civil Engineering	1	Senior	Building	15

7.8.3 Responses to Questions

Table 7-4 shows the average ratings of the system by evaluators in the different criteria. A detailed analysis of the various sections of the questionnaire is presented below. The main sections of the questionnaire were:

Buildability information communication: A high percentage (78%) for the first question (How well does the system facilitate the clarification of design information/details?) showed that the system can be used for clarifying design details to site teams efficiently. Most of the evaluators (in both sessions) gave this a rating of 3 or 4. Industry practitioners gave an average score of 3.6 while researchers gave an average score of 4.3 giving an overall score of 78% to question two (How well does the system support the communication between designers and contractors?). These scores indicate that VISCON can support communication between design and construction teams. The scores for the third question (How well does the system help in understanding how components can be assembled?) were slightly higher than the previous two, researchers gave it an average score of 4.4 and industry practitioners gave it an average score of 3.9 which results in an overall average of 82%. From this, it can be deduced that the system is a good tool for helping builders on site in understanding how different building components can be assembled. The use of the system to clarify interfaces between components was regarded to be less efficient compared with its ability to show how components can be assembled. The evaluators gave the system an overall average of 76% to question four (How well does the system help in clarifying the interfaces between components?). Question five in which the evaluators were asked to score how well the system can complement paper-based communication had a 79% positive response. Overall the system scored between 76 and 82 in supporting buildability problems.

Applicability to the construction industry: In this section, evaluators were asked to give their opinion on the applicability of the system to the construction industry. Question six aimed to gain feedback on the appropriateness of the visualisation tools

Table 7-4 Summary of Evaluators' Response to the evaluation questionnaire

a) Buildability information communication

Questions		Evaluators Rating (out of 5)			Overall %
		Resear. Averg.	Indust Averg.	Overall Averg.	
1	How well does the system facilitate the clarification of design information / details?	4.0	3.8	**3.9**	**78%**
2	How well does the system support the communication between designers and contractors?	4.3	3.6	**3.9**	**78%**
3	How well does the system help in understanding how components can be assembled?	4.4	3.9	**4.1**	**82%**
4	How well does the system help in clarifying the interfaces between components?	4.1	3.6	**3.8**	**76%**
5	How well the system complement the paper based communication tools?	4.1	3.8	**3.9**	**79%**

b) Applicability to the construction industry

6	How appropriate are the visualisation tools used in the system?	4.3	3.5	**3.8**	**76%**
7	How well does the system architecture support the flow of graphical information?	4.5	3.3	**3.8**	**75%**
8	How well does the system address the poor design details?	4.1	3.3	**3.6**	**72%**
9	How well does the system clarify conflicting design information?	4.1	3.7	**3.8**	**77%**
10	How well does the system increase the speed of the information flow during the construction?	3.9	3.2	**3.5**	**69%**
12	How convinced are you that construction industry professionals will accept the system?	3.8	3.2	**3.5**	**69%**

c) Management of the system

13	How well is the system architecture?	4.1	3.2	**3.5**	**71%**
14	How easy is the system to use?	4.1	3.2	**3.5**	**71%**
15	How well integrated are the different components of the system?	3.6	3.2	**3.4**	**67%**
16	*To what extent is the system flexible for choosing the most suitable of visualisation tool for clarifying and communicating information?*	3.5	3.6	**3.6**	**71%**

d) Efficiency

17	*How efficient is the visualisation system during the construction stage of a project?*	4.1	3.5	**3.7**	**74%**
18	How effective is the communication system during the construction stage of project?	4.1	3.2	**3.5**	**71%**

E) General

19	How confident are you with computers (generally)?	4.5	4.2	**4.3**	**86%**
20	How generic do you consider the system to be?	3.8	3.8	**3.8**	**76%**
21	What is your overall rating of the system?	4.1	3.7	**3.8**	**77%**

used in the system. To this question researchers gave an average score of 4.3 out of 5 while industry practitioners gave an average score of 3.5 out of 5 giving an overall average of 76%. The evaluators gave an overall average of 75% to the system architecture supporting the flow of graphical information. The system was considered by the participants in both sessions to be very good (77%) at addressing poor design details and clarifying design information. Therefore the results can be considered very satisfactory and the proposed system can be considered to have met one of the research objectives. With regard to the effectiveness of the system in improving the information flow during the construction stage of a facility, the evaluators rated the system with an overall average score of 3.5 (69%). This has been affected by the general belief that creating 3D models is time consuming. The evaluators gave the system an average of 3.5 out of 5 (69%) on the extent to which it can be adopted by construction practitioners to communicate graphical information between design and construction teams.

Management of the system: The architecture and the ease of use of the system were both rated at 71% while a somewhat lower ranking (67%) was given to the integration of the different components used in the system. Several suggestions and comments addressed the improvement of these tools and are discussed later in one of the proceeding sections. The evaluators were convinced that the flexibility in the choice of the most suitable visualisation tools to clarify and communicate information was good and gave an average score of 3.6 out of 5 (72%).

Efficiency: The use of the system was considered to be efficient during the construction stage of a project with an average score of 3.7 out of 5 (74%) while the communication component was given an average score of 3.5 out of 5 (71%).

General: Participants in both evaluation sessions considered the system to be very generic – an average of 76% supported this. The overall rating of the system was 3.8 out of 5 (77%), based on an average score of 4.1 by researcher 3.7 by practitioners.

7.9 DISCUSSION OF THE EVALUATION RESULTS

Despite the selection of evaluators in both sessions (researchers session and industry practitioners session) not being random due to the constraints mentioned earlier, they were however, sufficiently representative of potential end-users of the system, in that they possess adequate experience in building design and construction, or have been involved in the manufacturing of building components. The experience of the evaluators and their specialisations therefore can be considered as adequate for the assessment of the proposed system. This mix of expertise and background can also be considered as adequate for an objective evaluation and assessment of the proposed system.

The performance of VISCON was generally judged to be satisfactory. The rating of the questions in the questionnaire showed that VISCON can adequately perform the function for which it was designed and fulfiled the requirements. All the participants in the evaluation sessions were generally satisfied with the effectiveness of the system for communicating and clarifying design details that may cause some difficulty on site.

Most of those who took part in the evaluation were impressed with the quality of graphics used in the system. There was also an agreement that the graphics and the hyperlinks between the different models created to show how different building components interface and how they can be assembled help the design team to convey their design intent to site teams where 2D drawings and text information are not enough to do so. The industry practitioners, especially those who use 3D modelling, liked the system architecture and believe that it would be very helpful for people who currently use computer visualisation as well as those who are planning to introduce it in their organisations.

The low rating (69%) for the questions on the efficiency of the system in improving the speed of information flow during the construction stage was probably due to lack of understanding of how the communication system within VISCON works. The other question that received low scores (69%) was the one related to the usability of VISCON in the construction industry. On this point, all of the participants commented that the decision makers in the construction industry have the view that investment in computer visualisation is the field with least return. The other reason is that most of the decision makers came from paper-based school.

7.10 SUGGESTIONS FOR IMPROVEMENT AND COMMENTS

Table 7-5 Presents comments made by the participants in both evaluation sessions to improve the proposed system VISCON, and their general opinions about the system. The suggestions for improvement are mostly focused on the creation of the models in the system and the possibility of adding text information to them.

Table 7- 5: Suggestions for Improvement of and General Comments on VISCON

Suggestions for Improvement	Other Comments
• Attaching text information • Encapsulating more details • Detailed information representation • Increase the speed • Creation of 2D drawings from 3D models • Use software that can create images and animations with minimum input, time and effort • More detailed graphics in the prototype would demonstrate the usefulness of the system	• The use of AutoCAD make the system very useful in the industry • More confident visual graphics would improve the output • Generally good • General change in attitude to the benefits of producing 3D visualisation on a project • Share time costs by contractors & designers • Components design tends to be a long way down the construction, therefore, these components need to be provided by components supplier as they are labour intensive for architects. • The cost of visualisation should be shared between designers and constructors.

7.11 APPROPRIATENESS OF EVALUATION APPROACH

Both evaluation sessions were successful in providing feedback. The main comments were on how well the system coped with the communication of buildability graphical information. Although there were limitations associated with the system implementation, the evaluators were of the view that future improvements of the system would further facilitate the communication of graphical information between design and construction teams. The main points from the whole evaluation process were:

- The two sessions chosen with completely different considerations helped capture different perspectives on the system design;

- The questionnaire covered all major aspects of the system that needed to be tested and was useful in covering all essential feedback from the evaluators;

- Evaluators in the construction industry session had considerable experience in the field which ensured a relatively accurate assessment of the system;

- Both groups of evaluators were confident in the use of computers (86%). Finding people with the right level of computer knowledge is vital for the evaluation of a computerised system. The evaluation approach was correct in this regard, although it is recognised that in a real construction setting, not all team participants may be computer-literate.

The evaluation approach had some limitations with regard to the following:

- The researchers' evaluation should have been conducted earlier, making it more 'formative' in informing the second session;

- If 2D drawings used for creating 3D models were presented, it would have helped the evaluators to understand the concept behind the development of VISCON and how models might help the design intent to be conveyed easier and faster than from 2D drawings. This was not possible due to time constraints.

7.12 ANTICIPATED BENEFITS WITH VISCON

Although there is room for improvement, the prototype system VISCON provided an effective tool for communicating design information related to buildability between design and construction teams. Its effectiveness was proven through the questionnaire results. The average rankings of the questions in the four sections (from both evaluations) are:

Buildability information communication: (79%)

Applicability to the construction industry: (73%)

Management of system: (70%)

Efficiency: (73%)

Overall ranking: (77%).

Through the evaluation of the system, several practical benefits were demonstrated. These include::

- The commercial packages used in VISCON are tailored for the construction industry practitioners' need, thus savings in the form of time and cost can be expected.

- The development of the system within an established framework ensures that such a development is not done on an ad-hoc basis. This will allow the construction industry practitioners to use the system in situations suitable to their business; as a result the business may become more competitive.

- The use of VRML to present interfaces between different building components and 3D animations to show how these components can be assembled, can reduce buildability problems caused by the misunderstanding of design information. There are big benefits that can be gained from using VISCON, these benefits include but are not limited to reducing waste, rework, and cost; and delivering a high quality product.

- The development and implementation of the system were carried out on a PC with standard hardware within a window environment. This ensured that the developed product is within the reach of most construction firms.

- The participants in the industry survey, which was the basis for the system development, have become aware of recent technological advances which can help their business.

- The communication and collaboration tools used in the system ensures that the communication and collaboration in the construction sector is improved resulting in better productivity. The developed system covered important areas such as transfer of the design information between the design and construction teams to reduce the amount of rework caused by improper information communication.

Nevertheless there are still limitations in using the VISCON system. The following section discusses these limitations.

7.13 LIMITATIONS OF VISCON

Comments made by the evaluation participants have highlighted some of the limitations of the system, which include:

- Although the main aim of the system is the communication of graphical information, the system does not support textual information;

- 3D animations, 3D modelling and rendering requires powerful computers to work at reasonable speed and efficiency.

- 3D models need to be created using one of 3D CAD modelling software then exported to VRML. This process is not straightforward which can lead to poorly formatted and inefficient VRML files.

- Lack of texture in VRML made the models less realistic.

7.14 BARRIERS TO THE USE OF VISCON IN CONSTRUCTION INDSUTRY

The major barriers that may restrict the benefits that could be gained from the use of VISCON in the construction industry are as follows:

- Lack of knowledge of what computer visualisation can provide among construction industry professionals especially decision-makers, and the attitudes such as "we have never done that before" and "this is what we did on the last job and it worked then, so why do something different now?";

- The real or perceived high cost of advanced computer graphics, especially in the high cost of software for the organisation who do not use advanced CAD and visualisation software such as 3D modelling and rendering;

- The time required to adequately train staff in the use of computer systems.

7.15 SUMMARY

This chapter described the evaluation of the VISCON prototype system, in two sessions with academics and industry practitioners. The evaluation period for industry practitioners was rather lengthy and difficult because it was not easy to get a sufficient number of participants. The system has been evaluated in four key areas: its applicability to a buildability problem case, applicability to the construction industry, management, and efficiency.

In conclusion it can be said that the evaluation was a success. Although the system has some limitations, the evaluation results have shown that the system effectively supports buildability information communication. Overall, experts in the construction industry and the researchers who participated in the system evaluation have rated VISCON performance satisfactory.

The next chapter presents the summary and conclusions of the research project presented in the previous chapters of this thesis. It discusses contributions made by this research; recommendations for further work that can be done to the proposed system and further research that can be conducted in continuation of this research.

Chapter Eight
Summary and Conclusions

CHAPTER EIGHT

8 SUMMARY AND CONCLUSIONS

8.1 INTRODUCTION

This chapter concludes the research project, which focused on the use of computer visualisation to communicate design information in order to minimise buildability problems caused by misunderstanding of graphical information. The investigation resulted in the development of a visualisation and communication system architecture for supporting buildability. This chapter summarises the findings of the research, in terms of development, implementation and evaluation of the resulting prototype (VSICON) system. It concludes that VRML models and 3D animations can provide effective tools to clarify design details to site team members. The chapter ends by making recommendations for further work.

8.2 FINDINGS REGARDING THE RESEARCH QUESTIONS

The aim of the research project was to develop a visualisation and communication environment that would assist design teams in communicating design details that may be problematic for construction teams. The investigation was based on the need for a tool that facilitates detail design information communication. It focused on the development of a conceptual model for the use of computer visualisation communication and the development of a prototype system based on this conceptual model. Various tasks and strategies were adopted to achieve the defined objectives of the research. These included: extensive literature review, an industry survey, and participation at seminars and conferences to interact with other researchers and professionals in a similar research area.

The findings responded to the research questions in the following way:

- *Are traditional information tools adequate to communicate design information to construction teams?*

The design process and its related information, buildability, communication and visualisation tools, and their use in construction industry were reviewed. The review revealed that traditional visualisation tools are not adequate for clarifying design details especially those related to buildability problems. The review on computer visualisation and communication and design process revealed that current use of computer visualisation in the construction industry is mainly at conceptual design stage. Designers use computer visualisation as a presentation tool to explain their design intent to clients. The literature also suggested that there is a need for adopting computer visualisation as a tool for the exchange of design information related to buildability problems at the construction stage of a facility, current research efforts do not address the issue of the industry needs that computer visualisation can fulfil.

- *What are the uses of and attitudes towards, computer visualisation and communication tools within the construction industry?*

From above, the development of a prototype system, for the use of computer visualisation to communicate design information is, therefore, essential for improving communication/collaboration in the construction industry. However, this had to be preceded by an investigation into the current use of computer visualisation and buildability problems that occur during the construction stage of a building. Therefore, an industry survey has been conducted to achieve this aim. The survey provided a systematic examination of the experience and views of contractors and consultants on the use of computer visualisation as a tool for communication. The survey indicated that the use of computer visualisation was very low especially as a tool to communicate design information between designers and site-teams. The use of e-mail and data transfer was high and well established. As a communication media in the construction industry, their benefits have become well know to the majority of the construction industry professionals.

- *What are the buildability problems and their causes?*

The industry survey also included buildability problems caused by the lack of proper communication tools. Buildability problems (interfaces between components and difficult assemblies) were widely experienced in some areas such as cladding, roofs and services installations. The most common methods and tools used to clarify design details between designer and site-teams are the traditional ones such as 2-D drawings, face-to-face meetings, written statements and the use of a telephone and/or fax. Designers and contractors are accustomed to these methods and tools and find them easier to use which do not require special skills. However, as discussed earlier, these methods and tools were not considered adequate and fast enough in communicating requests for information and for requesting clarifications on some designs.

- *How would computer visualisation and communication tools help in dealing with buildability problems?*

Both the questionnaire and case studies results, along with findings from the literature survey revealed the lack of appropriate systems that may minimise these problems. A conceptual model behind the development of a prototype system for information visualisation and communication during the construction stage was developed. The model development took into consideration issues that have risen from the field investigations. A buildability graphical information flow framework was also developed. The proposed system combines both approaches for communication and information representation. The VISCON (computer visualisation support for buildability) environment provides support for general information sharing in the context of a collaborative building project. This prototype is Web based and can be accessed from any site. This will allow for construction information to be readily communicated between head offices and construction sites and any other locations to provide better visualisation of design details. This will ensure that information is communicated in a much better and clearer format. The resulting system architecture is comprised of three parts as follows:

The Modeller: The modeller component is responsible for mapping the data into a view model, which is an abstract representation of the scene to be rendered. This process is usually carried out in design team PCs. In the modeller, the design team generate the required visualisation for the part of the design that needs to be clarified.

The Data Store and Communicator (the Server): The data store and communicator (the server) can be either on the design team server, or wherever the Internet is available with sufficient space on server. It links the user's or the client's PC to the modeller's PC. The server works as the store for data input by the design and site teams. The design team information can be either graphical or textual depending on what the team considers necessary for constructing a specific component in addition to the standard information provided. In addition to this information, the design team should input any other material to reply to the site team's requests.

The User (Client): The users of the system are the design team and site team members. The system was developed assuming that there are PCs on the construction site with links to the Internet or Intranet. The PC should run DWF Viewer or any other Web format that can view CAD drawings, Cosmo player or any other VRML browser to view VRML models, Media player or any other animation player to view 3D animations, and a DWG Viewer to view CAD drawings.

The implementation stage revealed that the assembly of building components and their interfaces can thoroughly be investigated and studied. It also revealed that any missing design information can be discovered at an early stage. Several case studies for different building projects were used to demonstrate how the system can be used. These case studies were presented to evaluators to test the proposed system (VISCON). The system was evaluated by academics and construction industry practitioners. Some of their comments were useful to improve the system, while others may be implemented in the future with further development. The evaluation confirmed that, in spite of the improvements required to make the system more robust, it does proffer many benefits to construction industry practitioners to eliminate interface and assembly of building components problems.

8.3 GENERAL CONCLUSION

The following conclusions can be drawn from the research:

- The proposed system is a computer network-based, therefore it implies that users have access to the technology and the necessary knowledge to use it. The proposed system presents several advantages over conventional methods of communication and collaboration. In the latter, all the members of the team must be located in the same physical space. It is obvious that phone communication and teleconferencing along with facsimile could be used to support conventional gatherings. Unfortunately, these methods (facsimiles in particular) do not aid the unified databases of a project but rather cause a paper reproduction of project information. The proposed system overcomes these limitations; the users of the system could be located virtually anywhere there is access to global area network or local area network (LAN).

- VRML modelling and animations are good tools for advancing the use of computer visualisation in the construction industry. Integration of the VISCON system in the design and construction process will reduce the gap between the two. The system developed would help create, with relatively little effort, 3D animations showing how construction details should be assembled to avoid building failures due to contractors not understanding the details as presented in conventional, two-dimensional representations, particularly, how they come together at joints. VRML possesses potential application in assisting practitioners to understand more about the construction process and buildability analysis.

- It is probably better to have good technical and engineering technicians as users to the system rather than 3D CAD modellers as engineers have knowledge of details and construction aspects whereas a CAD technician's expertise is limited to software operation.

- VRML allows easy access to virtual reality models over the Web. A Web user can download a VRML file, navigate through it and interact with the models in real time.

- The legal and social implications of a paperless design and construction process are not yet completely understood by the industry as a whole, although VRML shows a promise as a medium for communicating building design in construction documents.

- Once the model has been created, it offers potential for off-site collaborative group work and also an effective environment in which the problems can be studied and their solutions evaluated.

- Visualisation based approaches can be more powerful than paper-based approaches because they support professionals in co-ordinating work and related information on projects by making face-to-face discussions more effective. Computer visualisation reduces the gap between what is drawn and what is built.

8.4 FURTHER RESEARCH

This research project has revealed a number of areas for further research and development. These are discussed with respect to the prototype application, problems associated with buildability that arise during the construction stage of a project, their causes, and visualisation use in the construction industry.

8.4.1 VISCON Prototype

A number of ways in which the VISCON prototype system can be enhanced include the following:

1. Further improvements to the system with respect to:

- Using more advanced 3D modelling, rendering, animation and VRML software;

- Creating a video link to a construction site using a digital camera or camcorder to take pictures and video clips of problems caused by improper design information;

- Implementation of 3D sketching tools to create 3D computer models of building components;

- Use of wireless communication and mobile multimedia equipment. This will make VISCON offer site activities new possibilities for communication and "distance presence".

2. Further investigation of more possible design problems that construction and design teams may face in any particular construction stage and add more functions to the system to enable it to cope with more specific situations while retaining its generic features;

3. Further testing using a wide range of live projects is still necessary as the feedback from these can further demonstrate the system's applicability to different live scenarios;

4. Exploration of possible linkages with other packages, such as database systems. The database will contain information about the location of the building components and the materials and their specifications. From the VRML model, the database will be queried to access other non-graphical information about the construction project.

8.4.2 Visualisation, Communication and Collaboration in the Construction Industry

Areas for further research with respect to collaboration and communication between design and construction teams to solve design problems that may arise during the design and construction process include:

1. Planning construction projects involves operations that range from making decisions for the selection of major assemblies and the resources needed to implement them, to daily written instructions for a small crew. This planning process can be broken down into micro and macro-planning processes. Macro-planning involves selecting major strategies, reviewing the design for buildability, site planning etc. 3D product model of the proposed facility would help decision makers at this stage to develop planning sequences and enable the user to check design buildability, select methods based on space and accessibility constraints and assign resources based on availability.

2. The use of visualisation can be extended to facilities management for remote operations, fault detection and safety checks;

3. The development of a comprehensive communication and collaboration system that not only organise the communication and collaboration process but also records the design problems that arise and the solutions reached;

4. Collaboration is needed almost throughout the whole construction process however the level of participation from the different disciplines can vary from one stage to the other. Therefore, the development of the collaboration tools and techniques geared explicitly for different construction stages is needed.

8.4.3 Implementation of Computer Visualisation Tools in the Construction Industry

Future research in the context of the use of computer visualisation tools in the construction industry would include the following:

1. Development of strategies for the application of computer visualisation from the perspectives of both the construction process and construction participants. The construction industry is going through several changes in the technological and processes area for creating construction documentation. The industry and more specifically individual companies must look at other parameters and aspects of the construction communication process other than technology. Production and profitability play a large factor in any construction project. Can the documents be generated at a specific rate in order to sustain profit within the project guidelines? Can the incorporation of technology make the production process less time consuming and without technological headaches? These are the questions that most AEC professionals are asking before the technological switch will take place in their business.

2. Research should be conducted into integrating heterogeneous CAD tools that are being used by different disciplines in a construction project. CAD systems are the source of most graphical data. Many of the commercial CAD systems used in the construction industry are primarily geometry modellers and used several file formats (3DS, DXF, OBJ, etc.). These file formats do not solve the problems associated with file transfer, therefore further researcher is needed in file format standardisation for both 2D and 3D information.

8.5 SUMMARY OF RESEARCH ACHIEVEMENTS

This research has identified the need to pay more attention to improve the way in which graphical information is conveyed between design and construction teams in order to reduce rework, cost and time. The main achievements of this research can be summarised as follows:

- Review of buildability problems and their causes during the construction stage of a facility;

- The development of a system architecture for a computer visualisation tool for buildability (VISCON);

- Implementation and validation of the proposed system (VISCON) through the use of a number of case studies. It was found to be useful and demonstrated that computer visualisation tools provide considerable potential in improving information clarity and also a new way of visualising and solving design problems that arise during the construction stage of a project. It also demonstrated the ease of use of the proposed system, its efficiency and applicability in the construction industry.

8.6 CLOSING COMMENTS

Modern CAD technology can be a very useful tool in the design of buildings and their components, and the exchange of information within the construction team. There are several benefits to be gained, in terms of eliminating waste and rework from using this technology for prototyping and rapidly exchanging information on design changes (Latham, 1998). Computer visualisation has become the field that designers are currently seeking to exploit as a new technology to cope with a rapidly changing construction industry. Project information visualisation is not only important at the design stage but it is also becoming increasingly important at construction stage. It can be a valuable tool to enhance present systems in the areas of construction sequence, equipment access, and work planning. In addition to that, visualisation with communication could create the necessary links between site and design teams to collaborate to solve buildability problems that may arise during construction.

The path from CAD to building assembly shows how VISCON can easily be integrated as an efficient tool within established CAD environments. The research documented in this thesis has demonstrated how VRML and 3D animations can be used to clarify design details that may be problematic to site teams as a result of insufficient 2D graphics and written information. The prototype system (VISCON) has illustrated the key features of such visualisation tools that can be used to show how some building components can be assembled and how different building components interface. The construction industry needs to take advantage of the approach proposed in this thesis .as it represents a significant improvement over existing approaches. The outlined structures and procedures can easily be adopted by construction industry practitioners to save time and costs of buildings construction.

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Appendices

APPENDICES

APPENDIX A: QUESTIONNAIRE SURVEY COVERING LETTER

Department of Civil and Building Engineering
Loughborough University
Loughborough Leicestershire LE11 3TU UK
☎ ++44 (0)1509 263171 Ext. 4140
Fax: ++44 (0)1509 223981

Loughborough University

Dear Sir /Madam:

I am conducting a survey on information communication during construction process of medium to high rise building blocks, as part of a research project at Loughborough University.

I would be grateful that if you could fill in the enclosed questionnaire and return it back in the next few days using the enclosed self addressed envelope. It is estimated that it will take about fifteen minutes to complete the questionnaire.

Thank you for your time and I would be happy to send you a summary of the results when they are published if you would like to receive them.

Yours faithfully,

A. Ganah

APPENDIX B: INDUSTRY SURVEY QUESTIONNAIRE

Questionnaire sent out to the top 50 UK contractors

Information Communication during Construction Process Survey

A. General Information

1. Size of the organisation

❑ 1-10 Employees ❑ 11-24 Employees ❑ 25-49 Employees ❑ 50-99Employees

❑ 100-249 Employees ❑ 250-499 Employees ❑ 500-999 Employees ❑ Over 1000 Employees

2. How many years of experience does your organisation have in the construction of medium to high rise buildings? ________________Years

B. Visualisation and Communication Tools

3. What type of computer visualisation do you have on the site?

❑ None ❑ Rendered Images ❑ Animation ❑ 3-D CAD Models

❑ Virtual Reality Simulation ❑ VRML-Presentation ❑ Others (please specify ....

4. How often and with whom do you use the following communication techniques?
(1=Rarely 2=Sometimes 3= Frequently as appropriate).

	Communication Medium	Organisation to contact with				
		The Organisation Head Office	Design Offices	Subcontractor Offices	Supply Chain	Other (please specify) ....
1-	E-mail					
2-	Video Conferencing					
3-	Electronic Data Transfer					
4-	Virtual Reality					
5-	Internet/ Intranet					
6-	Other (please specify)					

C. Construction process problems

5. ***Below are building components associated with possible buildability problems, could you please rate them in order of occurrence in projects that your company has carried out.*** *(1=Rarely 2=Sometimes 3= Frequently as appropriate)*

No.	Building area	Problem		
		Interfaces between components	Difficult assembly	Other (please specify) ....
1-	Substructure			
2-	Slabs			
3-	Frame			
4-	Stairs			
5-	Core			
6-	Roof			
7-	Cladding			
8-	Internal walls			
9-	Features			
10-	Electrical Instl.			
11-	Plumbing works			
12-	Mechanical Instl.			
13-	Finishes			
14-	Other (please specify)			

6. ***According to your experience what are the possible reasons for these problems.*** (Please tick)

No.	Building area	Reasons for requesting clarification						
		Poor design details	Inadequate specifications	Conflicting design information	Novel design features	Innovative construction process / assembly	One-off design component / assembly	
1-	Substructure							
2-	Slabs							
3-	Frame							
4-	Stairs							
5-	Core							
6-	Roof							
7-	Cladding							
8-	Internal walls							
9-	Features							
10-	Electrical Inst.							
11-	Plumbing works							
12-	Mechanical Inst.							
13-	Finishes							
14-	Other (ple. specify)							

7. ***There are several methods used to clarify details during construction, which of the following does your organisation use?*** *(1=Rarely 2=Sometimes 3= Frequently as appropriate)*

No.	**Building area**	**Methods used to deliver solutions**												**Are these methods adequate (Yes/No)**
		Written Statements	**2-D Drawings**	**Physical Models**	**Face to face**	**3-D CAD Models**	**Rendered Images**	**Video Animations**	**4-D CAD (Simulation)**	**Virtual Reality Simulation**	**VRML-Presentation**	**Presentation on the Internet**	**Other (P/S) ....**	
1-	**Substructure**													
2-	**Slabs**													
3-	**Frame**													
4-	**Stairs**													
5-	**Core**													
6-	**Roof**													
7-	**Cladding**													
8-	**Internal walls**													
9-	**Features**													
10-	**Electrical Inst.**													
11-	**Plumbing works**													
12-	**Mechanical Inst.**													
13-	**Finishes**													
14-	**Other** (please specify)..........													

8. ***What do you think is the best way to clarify details to the construction team?***
(1=Rarely 2=Sometimes 3= Frequently as appropriate)

No.	Building area	**Methods might be used to deliver solutions**											**Other (P/S) ....**
		Written Statements	**2-D Drawings**	**Physical Models**	**Face to face meeting**	**3-D CAD Models**	**Rendered Images**	**Video Animations**	**4-D CAD (Simulation)**	**Virtual Reality Simulation**	**VRML-Presentation**	**Presentation on the Internet**	
1-	Substructure												
2-	**Slabs**												
3-	**Frame**												
4-	**Stairs**												
5-	**Core**												
6-	**Roof**												
7-	**Cladding**												
8-	**Internal walls**												
9-	**Features**												
10-	**Electrical Inst.**												
11-	**Plumbing works**												
12-	**Mechanical Inst.**												
13-	**Finishes**												
14-	**Other** (please specify)												

9. ***It may be necessary to make changes to some design details on site according to your experience could you please assess how often there is a need to do so during construction process?***
☐ Never ☐ Rarely ☐ Sometimes ☐ Frequently

10. ***How do you issue requests for information?***
☐ Formal channels ☐ Informal/ Direct Contacts ☐ Both ☐ Other (please specify..................)

11. ***How long does it usually take to receive replies to requests for information?***
☐ Several Hours ☐ Several Days ☐ a Week ☐ Several weeks

12. ***How adequate is the communication between you and the designers in obtaining the necessary information to perform your job?***
☐ Very poor ☐ Poor ☐ Fair ☐ Good ☐ Very good

13. ***How often do you receive conflicting instructions from the designers?***
☐ Usually ☐ Sometimes ☐ Rarely ☐ Never

14. ***What percentage does the lack of information contribute toward the total delay in construction?***
☐ 0% ☐ 1 - 10% ☐ 11-30% ☐ 31-50% ☐ Over 50%

15. ***How often are you asked to work with the design team in solving design problems that arise on site?***
☐ Never ☐ Rarely ☐ Sometimes ☐ Frequently

D. Assessment

16. ***Do you think that computer visualisation could improve communication during the construction stage of a project?***
☐ Negative effect ☐ No effect ☐ A little ☐ Much ☐ Very much

17. ***Would you like to be kept informed about this research project?***
☐ No ☐ Yes **(Please enclose your name and address).**

18. ***Are there any other comments you would like to add?***
....
....
....
....

Thank you for completing this questionnaire.
Please return it using the envelope provided.

Questionnaire sent out to the top 50 UK consultants

Information Communication during Construction Process Survey

A. General Information

1. Type of the organisation

☐ Architectural Design ☐ Structural Design ☐ Services Design ☐ Other (please specify) ....

2. Size of the organisation

☐ 1-10 Employees ☐ 11-24 Employees ☐ 25-49 Employees ☐ 50-99 Employees

☐ 100-249 Employees ☐ 250-499 Employees ☐ 500-999 Employees ☐ Over 1000 Employees

3. How many years of experience does your organisation have in the design of medium to high rise building blocks? _______ ***Years***

B. Visualisation and communication Tools

4. At which design stage does your organisation use computer visualisation and how often? (1=Rarely 2=Sometimes 3= Frequently as appropriate)

No	Stage	Visualisation Tool						Adequacy (Yes/No)
		3-D CAD Models	Rendered Images	Animation	Virtual Reality Simulation	VRML-Presentation	Others (please. specify)	
1-	Conceptual design							
2-	Detailed design							
3-	Services design							
4-	Design Analysis							
5-	Production informtn.							
6-	Presentation							
7-	Project planning							
8-	Collaboration							
9-	Communication							
10	Other (please specify)							

5. At which stage of design does your organisation use the following communication techniques? *(1=Rarely 2=Sometimes 3= Frequently as appropriate)*

No	Communication medium	Stage of Design							Adequacy (Yes/No)
		Conceptual design	Detailed design	Services Design	Production Information	Project Planning	Commun-ication	Other	
1-	E-mail								
2-	Video Conferencing								
3-	Electronic Data Transfer								
4-	Virtual Reality								
5-	Internet/ Intranet								
6-	Other (please specify)								

B. Construction process problems

6. Below are building components associated with possible buildability problems, could you please rate them in order of occurrence in projects that your company has carried out. *(1=Rarely 2=Sometimes 3= Frequently as appropriate)*

No.	Building area	Problem		
		Interfaces between components	Difficult assembly	Other ....
1-	Substructure			
2-	Slabs			
3-	Frame			
4-	Stairs			
5-	Core			
6-	Roof			
7-	Cladding			
8-	Internal walls			
9-	Features			
10-	Electrical Inst.			
11-	Plumbing works			
12-	Mechanical Inst.			
13-	Finishes			
14-	Other (please specify)			

7. According to your experience what are the possible reasons for these problems.
(Please tick)

No.	Building area	Reasons for requesting clarifications						
		Lack of experience in reading design drawings	Misunder-standing of the design details	Conflicting design information	Novel design features	Innovative constructio n process / assembly	One-off design component/ assembly	Other ....
1-	Substructure							
2-	Slabs							
3-	Frame							
4-	Stairs							
5-	Core							
6-	Roof							
7-	Cladding							
8-	Internal walls							
9-	Features							
10-	Electrical Inst.							
11-	Plumbing works							
12-	Mechanical Inst.							
13-	Finishes							
14-	Other (p/s)							

8. There are several methods used to clarify details, which of the following does your organisation use and how often? *(1=Rarely 2=Sometimes 3= Frequently as appropriate)*

No	Building area	Methods used to deliver solutions												
		Written Statements	2-D Drawings	Physical Models	Face to face meetings	3-D CAD Models	Rendered Images	Video Animations	4-D CAD (Simulation)	Virtual Reality Simulation	VRML-Presentation	Presentation on the Internet	Other (P/S)	Is it adequate (Yes/No)
1-	Substructure													
2-	Slabs													
3-	Frame													
4-	Stairs													
5-	Core													
6-	Roof													
7-	Cladding													
8-	Internal walls													
9-	Features													
10-	Electrical Inst.													
11-	Plumbing works													
12-	Mechanical Inst.													
13	Finishes													
14	Other (p/ s)													

9. Sometimes contractors may ignore or change some design details, how often do you ensure contractors' compliance with your design details?

☐ Rarely ☐ Sometimes ☐ Frequently ☐ Always

10. How long does it take you to respond to information requested by the construction team?

☐ Minutes/ Hours ☐ Few Days ☐ a Week ☐ Several weeks

11. What percentage does the lack of information contribute toward the total delay in construction?

☐ 0% ☐ 1 - 10% ☐ 11-30% ☐ 31-50% ☐ Over 50%

D. Collaboration

12. How often do you work with the site team in solving design problems that arise on site?

☐ Never ☐ Rarely ☐ Sometimes ☐ Frequently

13. How often do you collaborate with other design disciplines in design of projects?

☐ Never ☐ Rarely ☐ Sometimes ☐ Frequently

E. Assessment

14. To what extent do you think that computer visualisation could improve communication during the construction stage of a project?

☐ Negative effect ☐ No effect ☐ A little ☐ Much ☐ Very much

15. Would you like to be kept informed about this research project?

☐ No ☐ Yes (Please enclose name and address where the information should be sent)

16. Are there any other comments you would like to add?

....

....

....

Thank you for completing this questionnaire.
Please return it using the envelope provided.

APPENDIX C: CASE STUDIES TEMPLATE

Information Communication during Construction Stage
Case Study ( )

The case studies should answer the following questions:

1. Why are visualisation tools (VR, VRML, animation, and rendered images) not used widely?
2. Why are Video conferencing and VR not used as communication media?
3. How and why stairs, roof, cladding and services installations are major problems?
4. How and why are interfaces between components a major problem associated with most buildability areas?
5. How and why is difficult assembly a major problem associated with roofs? To what extent does the problem differ from one project to another?
6. How and why are conflicting design information and poor design details major causes for buildability problems?
7. How and why are written statements, 2-D drawings and face to face meetings the most common methods used to clarify buildability problems?
8. Why is there a need for changing or recommending changes to design details during construction process other than client requests and how are these changes carried out?
9. Are critical activities identified during the design stage?
10. Is there a distinction between activities, which are inherently difficult to perform, and those, which a contractor possessing the appropriate skills should be able to manage without undue difficulty?
11. How are information requests issued (the routes or steps that should be followed to issue requests for information)?
12. What is the draw back of using the formal and informal communication channels?
13. How to deal with conflicting instructions and why are there conflicting instructions?
14. How does the design and site teams collaborate to solve design problems?

15. To what extent can construction professionals use new visualisation technologies to improve communication?
16. How readily can the organisation adopt a new technology that improves its operations?
17. How can the skills and knowledge of site operatives regarding how building components fit together and interpreting construction drawings be assessed?

APPENDIX D: EVALUATION QUESTIONNAIRE

Computer Visualisation Support for Buildability

Evaluation Questionnaire

This evaluation questionnaire should be completed following a demonstration of the prototype system.

Information about the participant

Your position (e.g. project manager, design consultant, engineer) ___________

Area of experience (e.g. civil engineering, building, etc) ________________

Experience in the construction industry (years) _______

Evaluation of the Prototype System:

(*Please put a tick in the box that best represents your assessment of a question*)

The System

		Ranking *1 is poor & 5 is excellent*				
		1	2	3	4	5
1	How well does the system facilitate the clarification of design information / details?					
2	How well does the system support the communication between designers and contractors?					
3	How well does the system help in understanding how components can be assembled?					
4	How well does the system help in clarifying the interfaces between components?					
5	How well the system complement the paper based communication tools?					

Applicability to construction industry

6	How appropriate are the visualisation tools used in the system?					
7	How well does the system architecture support the flow of graphical information?					
8	How well does the system address the poor design details?					
9	How well does the system eliminate conflicting design information?					
10	How well does the system increase the speed of the information flow during the construction?					
12	How convinced are you that construction industry professionals will accept the system?					

MANAGEMENT OF THE SYSTEM

		1	2	3	4	5
13	How well is the system architecture?					
14	How easy is the system to use?					
15	How well integrated are the different components of the system?					
16	To what extent is the system flexible for choosing the most suitable of visualisation tool for clarifying and communicating information?					

EFFICIENCY

17	How efficient is the visualisation system during the construction stage of a project?					
18	How effective is the communication system during the construction stage of project?					

GENERAL

19	How confident are you with computers (generally)?					
20	How generic do you consider the system to be?					
21	What is your overall rating of the system?					

General Comments

1. In what ways can the system be improved?

____

____

____

____

2. Further comments:

____

____

____

____

APPENDIX E: PUBLICATIONS LIST

This appendix contains publications list

Refereed Conference Papers

Ganah, A., Anumba, C. and Bouchlaghem, N., (2000), "The Use of Visualisation to Communicate Design Information to Construction Sites", *ARCOM 16th Annual Conference*, Glasgow, pp.833-842.

Ganah, A. Anumba, C. and Bouchlaghem, N., (2001), "Computer Visualisation Support for Site Level Operations", *International Postgraduate Research in the Built and Human Environment,* Salford, 15-16 March 2001, pp. 541-552.

Ganah, A. Anumba, C. J. and Bouchlaghem, N. M (2001),"Computer Visualisation as a Communication Tool in the Construction Industry " *5th International Conference Information Visualisation,* London, 27 - 29 July 2001, pp. 679-683.

Ganah, A. Anumba, C. J. and Bouchlaghem, N. M (2001), "A Survey on the use of Visualisation tools to communicate Buildability Information, *COBRA 2001 Conference*, Glasgow, 2-4 September, pp. 721-731.