Literature Review
Report Project 2002-024-B/Report 01-2003

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Research Program No: B

Program Name:	Sustainable Assets
Project No:	2002-024-B
Project Name:	Team Collaboration in High Bandwidth Virtual Environments
Date:	October 2003

Distribution List

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1. PREFACE

This report documents the results of the Literature Review for the CRC project ‘Team Collaboration in High Band-with Virtual Environments’. It provides information about the three principal areas under review: collaborative design, collaborative design technologies and multi-view modelling research. The main focus of the research into team collaboration is at the intersection between communications technologies and tools for supporting conceptual design. In addition, the project is addressing the area of multi-user design modelling, a topic that is at the leading edge of high bandwidth virtual environments research.

The Literature Review has a two aims: the first is to establish knowledge about the current status of the research that will inform the project aims and shape the research program; the second is to provide relevant information to the project industry partners in order to guide their future planning in the introduction of new technologies to support remotely located team work.

In order to make the results more accessible and with a view to informing the wider industrial community, a web site is under development. A set of research reports where further information is provided may also be found on this site. The site will be updated during the course of the project as new information is identified.

2. EXECUTIVE SUMMARY

There are many studies that reveal the nature of design thinking and the nature of conceptual design as distinct from detailed or embodiment design. The results can assist in our understanding of how the process of design can be supported and how new technologies can be introduced into the workplace. Existing studies provide limited information about the nature of collaborative design as it takes place on the ground and in the actual working context. How to provide appropriate and effective of support for collaborative design information sharing across companies, countries and heterogeneous computer systems is a key issue. As data are passed between designers and the computer systems they employ, many exchanges are made. These exchanges may be used to establish measures of the benefits that new support systems can bring.

Collaboration support tools represent a fast growing section of the commercial software market place and a reasonable range of products are available. Many of them offer significant application to design for the support of distributed meetings by the provision of video and audio communications and the sharing of information, including collaborative sketching. The tools that specifically support 3D models and other very design specific features are less common and many of those are in prototype stages of development. A key question is to find viable ways of combining design information visualisation support with the collaboration support technologies that can be seen today. When collaborating, different views will need to be accessible at different times to all the collaborators. The architects may want to explain some ideas on their model, the structural engineers on their model and so on. However, there are issues of ownership when the structural engineer wants to manipulate the architect's model and vice versa. The modes of working, synchronous or asynchronous may have a bearing as in a synchronous session there is control of what is happening.

The key research questions in collaborative design are:

- How to obtain evidence about collaborative design as it takes place in practice
- How to understand the cross-country, cross-company, cross-culture issues
- How to establish measures of benefit for new support systems

The key research questions for collaboration technologies are:

- How to find principled ways of migrating single user conceptual design support systems to full collaborative conceptual design environments
- How to provide a shared sense of presence to the designer participants

The key research issues specific to the multi-view modelling are:

- What is represented in each model; what can be common to a number of models and what is specific to a discipline model
- How is consistency maintained among the models
- How to represent the models
- How to link the different models to agent systems that operate in the Virtual World

3. INTRODUCTION

The CRC Project 2002-024-B 'Team Collaboration in High Band-with Virtual Environments' is concerned with collaborative design using high bandwidth communication technology and concept design tools. The research addresses a gap in available evidence about the impact of introducing collaboration technologies into the design process. Thus, the project will contribute to knowledge about how architectural design and the construction industry may benefit. In order to understand the practical implications of introducing new digital tools on working practices, research into how designers work collaboratively using both traditional and digital media is being undertaken. This will involve a series of empirical studies in the work places of the collaborating partners in the project. Thus, the project looks at two aspects of collaboration in virtual environments:

- The processes that enable effective collaboration using high bandwidth communication technology
- The models that enable different disciplines to share their views using virtual design environments

The project is intended to benefit the industry partners in Australia by proposing more effective communication and collaboration in a global construction context. The starting point is a review of studies, tools and systems that have been developed throughout the world. An area of research and development but fundamental to the functionality of today's collaboration technologies is the network infrastructure available and the implications of bandwidth size for performance. This project will employ existing high bandwidth applications but will not be concerned explicitly with developing infrastructure technologies. The main focus of the research into team collaboration is at the intersection between communications technologies and tools for supporting conceptual design. In addition, the project is addressing the area of multi-user design modelling, a topic that is at the leading edge of high bandwidth virtual environments research.

The Literature Review has two main purposes: the first is to establish knowledge about the current status of collaboration tools for conceptual design that will inform the project aims and shape the research programme; the second is to provide relevant information to the project industry partners in order to guide their future planning in the introduction of new technologies to support remotely located team work.

This report documents the results of the literature review for the CRC project 'Team Collaboration in High Band-with Virtual Environments'. It provides information about the three principal areas under review: collaborative design, collaboration technologies and multi-view modelling research. In addition, empirical studies about the nature of collaborative conceptual design are relevant to our understanding of user requirements for design support environments. In order to make the results more accessible and with a view to informing the wider industrial community, a web site is under development. A set of research reports where further information is provided may also be found on this site. The site will evolve and be updated during the course of the project as new information is identified.

- Section 4 provides a brief account of the emergence of computer-supported collaborative work (CSCW) and the nature of collaboration and conceptual design.
- Section 5 presents research into collaborative design focusing on early conceptual design, the influence of the domain on the processes employed and empirical studies in these areas.
- Section 6 describes collaboration technologies in terms of tools for conceptual design, general-purpose systems for collaborative work and high band width environments for three- dimensional modelling in shared virtual spaces.
- Section 7 describes current research into multi-view modelling approaches including database and object oriented approaches, CAD systems, data representation and standardisation methods and system architectures.
- Section 8 Conclusions and Ongoing Work
- References are provided for each section at the end of the report. The supporting research reports for each topic are referenced in the text.

4. BACKGROUND

The beginnings of research into digital technologies for supporting human collaborative work can be traced to the 1960s with the early work at Stanford Research Institute into innovative interaction techniques. This research and the developments at XeroxPARC in the 1970s and 1980s, gave rise to what became known as user-centred design (Norman and Draper, 1986), an important research focus in an emerging field called Human Computer Interaction (HCI). Later, in the early 1990s, a branch of HCI developed into the research area of Computer Supported Cooperative Work (CSCW) and groupware technologies. Like HCI, CSCW is a multi-disciplinary field that has made significant contributions to the design of collaborative technologies. From a focus on small group support, the area has expanded into theories and technologies for organisational management. At the same time as the foundation theoretical research was emerging, applications to the domain disciplines from architecture and engineering to product design began to be developed and the ‘ownership’ of the field expanded rapidly. Today, there are numerous divergent perspectives and initiatives operating across many domains of expertise, most of which involve a high degree of inter-disciplinary work. A review of the background and scope of CSCW and related areas of research may be found in a paper by Grudin and Poltrock (1997).

Increasing the bandwidth of communication available to people who are working in remote locations is a current challenge to the IT research community. The technology bandwidth has a profound effect on what can be offered in respect of channels of communication such as making use of vision and gesture. However, the size of the bandwidth is not the main problem to be solved. There are many uncertainties as to the relative value of providing multiple channels for users who are working in a shared virtual space. Shared on-line drawing systems in which users can interact with each other’s drawings across the Internet are now available, but the problem of how to support the users’ awareness of one another in a situation where they are working at the same time (synchronously) are unresolved. Research into how to provide effective mutual awareness using 3D modelling techniques focuses on creating virtual representations of users that convey gaze, body movement and persona. (See for example Luciano et al, 2001;). At the same time as research into representing human participants in shared virtual spaces, other work into developing 3D views of product parts and assemblies and documents is taking place (e.g. Ragusa and Bochenek, 2001).

Collaborative tasks can be classified in ways that match individual, social and organizational situations: a basic classification is to view them as a combination of communication exchanges, information sharing processes and coordination or management tasks. In most team activities, whatever the domain, collaboration involves the interleaving of individual and group effort in a process of continuous information exchange. The coordination of such exchanges requires careful management particularly in complex design and engineering processes. This process is even harder to manage where it is carried out in remote geographical locations and with large time differences and mediated by a number of forms of technology from telephone to fax and email. The need for effective communication channels is vital to success and the nature of that communication is not always accessible to empirical investigation. A complex set of verbal and non-verbal methods of exchange take place that are not always easy to describe systematically.

"… singular-to-shared activities require considerable explicit and tacit communication between collaborators to be successful." (Snowdon, Churchill, Munro, 2001, p9).

Communication tasks that take place between people located in different time and geographical zones, and now a familiar part of the global economic and social scene, are enabled by the widespread availability of electronic mail. For ‘anywhere, anytime’ communication, email with associated document transfer facilities, addresses time zone differences and transfer of text, image and sound documentation across widely distributed locations. This means of exchanging information is now readily accessible and relatively easy to use to the point of being perceived as an essential and integral part of working and social life today. The whole process is, of course, a sequential, linear one, albeit often with very rapid turnaround of exchanges and materials that can give the feel of a simultaneous collaborative activity. It is often supplemented by telephone, fax and conventional postal services particularly where the bandwidth for transferring large amounts of documentation is low. Nevertheless, collaborative tasks, such as writing a book with as many as twenty five authors or more, is no longer a distant prospect, and expectations are already high of more capability to come in the immediate future.

A classification of collaborative activities into four types according to whether they take place at same or different time and place proposed by De Sanctis and Poole was applied by the CSCW community as the basis for considering the kinds of computer support that might be provided (De Sanctis and Poole, 1987). Figure 1 shows categories of media and tools used to support such tasks will be different according to those categories. Figure 2 shows studies that have been undertaken into the role of technologies for collaborative design may be classified in the same way.

	Same time	Different time
Same place	Electronic meeting support system	Workflow co-ordination system
Different place	Video conferencing	E-mail

Figure 1: Matrix of Collaboration: Media and Tools

	Same time	Different time
Same place	Delft Protocols Workshop Cross, Christiaans & Dorst 1996 Modelling Co-Creativity… Candy & Edmonds 2002	…Groupware Supported Workflow Atkinson & Lamb 1999 Workflow Systems.. Grinter, 2000
Different place	Supporting Collaboration… Shah, Candy & Edmonds 1998 Designing Collaborative Environments… Kvan & Candy, 2000	Sharing Information… Multi-Site Team Development Britton, Candy & Edmonds 2001

Figure 2: Matrix of Collaboration: Studies

5. COLLABORATIVE DESIGN

5.1 Conceptual design

How designers create ideas and realise them in tangible forms has challenged the design research community for many years (Lawson, 1980, 1994). In particular, the conceptual phase of design has been a focus of much research whether it is in engineering, architectural or product design. In conceptual design, designers determine the scope of a given problem and explore a range of possible solutions to a given brief or set of client requirements. Conceptual design usually involves tolerating a high degree of uncertainty during which designers generate ideas and express them as two- dimensional sketches using tools like pencil and paper (Qin, 2003).

Free-hand sketches have been recognized as having important roles in concept design but this is a partial view of the process. The design thinking process is both ill structured and goal oriented. Designing takes place in both a problem space and a solution space that evolve over time and inter-relate (Dorst). Conceptual design has also been described as a reflective practice. According to Schön, reflective practice is a learning and exploration process involving a number of iterations in which the designer generates potential solutions in a problem space that has a dynamic and an evolving nature (Schön,1983). Reflective practice takes place in conceptual phases of designing rather than in routine phases. It can be “reflection-in-action” where it is an integral part of the design process and usually not explicitly uttered, or “reflection-on-action”. Reflection-on -action is most often triggered by problems coming up during the design process. If there are no major problems there is unlikely to be any reflection of either kind.

French describes concept design as the most demanding aspect of the whole design process. He characterises it in the following way:

"[it] takes the statement of the problem and generates broad solutions to it in the form of schemes. It is the phase that makes the greatest demands on the designer and where there is the most scope for striking improvements. It is the phase where engineering, science, practical knowledge, production methods and commercial aspects need to be brought together and where the most important decisions are made."

Early design activity involves the formulation of solutions or concepts that meet client requirements before going on to detail and embodiment design. However, approaches to the whole design process and to conceptual design in particular, are currently undergoing rapid change in the direction indicated by French above. This may be partly a result of changes in market imperatives and partly a result of new technological support tools and methods. Conceptual design includes consideration of the requirements specification as well as generating the initial candidate designs. Bowman and Cooper characterise the task of the conceptual designer as, "to understand the customer's need, analyse it and produce a model of the possible solutions and present these for the customer's choice/acceptance". They also distinguish it from detail design thus, "The object, therefore, of concept design is to describe the total product, that of detail design to describe how that product might be made." (Bowman and Cooper, 1994, p12).

In architectural design research, free-hand sketches have been recognized as having important roles in the design process (Schon, 1983; Akin, 1986; Goldschmidt, 1991, 1994). Sketches, being an integral part of design, store the design solutions and also seem to be essential for recognizing conflicts and possibilities (Akin, 1978) as well as for revising and refining ideas, generating concepts and facilitating problem solving (Do et al., 2000). Therefore, design research has extensively examined the early stages (conceptual phase) of the design process and explored the way designers use sketches while designing (Akin, 1986; Schon, 1987; Goldschmidt, 1991; Goel, 1995; Suwa and Tversky, 1997).

Whilst the role of sketching is a particular focus whenever conceptual design is considered, it should be noted that conceptual design also involves additional processes including -- mental integration and synthesis of strategic knowledge which is supported by design experience, as well as the use of mental imagery for simulating the real world situations and solving problems. Thus the definition of the conceptual design phase cannot be limited to initial sketching activities.

5.2 Domain Differences

Goldschmidt (1996) proposes two main characterizations of the design domain: first, design as an art-oriented activity and second, design as an engineering-oriented pursuit. Architectural design can be more art-oriented, compared to industrial design; however the opposite way is possible depending on the design problem or project at hand. On the other hand significant differences occur between engineering and architectural conceptual design phases, such that engineering design usually involves the interaction of a team while architectural design needs more individual work. Thus, engineering oriented designs are associated with collaborative processes while architectural design is associated with concepts and sketches.

This makes the definition of conceptual design different for engineering versus architectural domains. Thus one has to consider the domain specific characteristics of the conceptual design phase to determine where it ends and where it begins.

Conceptual Design in the mechanical domain has been defined as having two stages (Wang et al., 2002): the first stage in which fuzzy customer requirements are mapped to functional specifications and the second stage where a design team tries to develop multiple alternative design solutions from functional specifications. Several research tools are being developed to satisfy the needs of the second stage and some examples are referred to in Wang et al., (2002).

In the engineering oriented design professions it is more common to generate ideas within a group of colleagues in, for example, initial brainstorming sessions. The concepts and multiple criteria solutions of individuals are then combined in order to construct the total design. However in architectural design, the conceptual phase has often been one person's responsibility (Lawson, 1996).

5.3 Team Design

The qualities of a good team design process have been defined in terms of communication behaviour and the communication environment. Communication behaviour involves the psychological modes and reactions of the team members, shared understanding, a shared language, general awareness of others and co-operation. In the engineering design domain, cognitive factors have been defined for distributed design.

Team designing using Schon's (1983; 1987) model of four activities; naming, framing, moving, and reflecting has been characterised by Valkenburg and Dorst (1998). The basic elements of design activities are the actions, and the kernel of the design ability is to make intelligent decisions about those actions. The results of these experimental actions are scrutinised by the designer, who reacts to this new state of his/her own making. The final design is a result of this interaction. In this 'reflective conversation with the situation', designers work by naming the relevant factors in the situation, framing a problem in a certain way, making moves toward a solution and evaluating those moves. They developed a coding scheme with these activities and analysed and pictured the team designing in two empirical studies. They state that the reflective practice way provides us with a language to communicate about difficult and subjective issues within the design project. For an account of the further developments of this work see Valkenburg, 2000.

In architectural design practice, the architect/designer needs to generate potential solutions to the design problem given that the problem space has a dynamic and an evolving nature. Semantic density and ambiguity of the design representations help the designer to develop the concepts continuously (Goel, 1995). Thus the sketches have been characterized as unstructured. Craig and Zimring (2000) propose to introduce this unstructured character of sketches to design collaboration in the conceptual phase. They claimed that the unstructured interactions between design students, in a collaborative online studio (CoOL which is a web based approach) might improve their individual and group thinking activity. Further it was hypothesized that open participation (on the web) would be fostered by a sense of community (perception and awareness of others as well), however the web based collaborative environment has failed to promote that. Same authors later discussed the collaborative design in shared virtual spaces (Craig and Zimring, 2002) referring to the role of unstructured verbal communication and graphic communication in virtual 3D space. The paper explores cognitive aspect of design, modes of communication, the context of sharing and presents an asynchronous collaborative system (IDT) as a means for supporting productive design exchanges.

In architectural design practice, the research group at Delft University of Technology, Netherlands devised the Architectural Collaborative Design (ACCOLADE) project which defines the qualities of a good collaborative design process, in terms of communication behaviour and communication environment. They also propose how those aspects should be developed (Stellingwerff and Verbeke, 2001).

Communication behaviour in the design domain is one of the key topics in collaborative design research. Communication behaviour involves the psychological modes and reactions of the team members, shared understanding, shared language, general awareness of others, co-operation etc. Valkenburg (1998) points out that the individual designers have to tune their personal understandings about the design content to achieve a shared understanding. In that paper, she builds a conceptual theoretical framework in order to try to capture the essence of designing within a team.

In the engineering design domain, cognitive factors have been defined for distributed design (Lang et al., 2002). The factors for collaborative processes may be listed as:

- Cognitive synchronization
- Developing shared meaning and shared memories
- Negotiation
- Communication of data, knowledge, information
- Planning of activities, tasks, methodologies
- Management of tasks

Some of those cognitive factors have been studied with mechanical engineering students (Stempfle and Schaub, 2002) in a protocol analysis study that examined the elements of thinking in design teams. In a laboratory condition, the design team's communications has been recorded and analysed sentence by sentence. The communicative actions have been classified as process related (planning of activities, tasks, methodologies, management of tasks) and content related activities (referring to the design activity, in terms of goal clarification, solution generation, analysis, evaluation, decision and control actions). The authors explored the general patterns in the team communication and problem solving process and analysed components of designers' communication behaviour and self reflection of the individuals.

Wang et al (2002) propose eight areas for future collaborative conceptual design research opportunities and challenges. The paper also presents detailed literature reviews of the existing research projects and applications in the area.

Collaborative workspaces for geographically distributed teams to support individual, social and meeting work modes have been proposed. There are four basic requirements for collaborative workspaces:

- Support for the work modes (individual, social or meeting modes)
- Categorization of the activity categories for easy access for the participants (work-related, people-related, meeting-related)
- Synchronous and asynchronous modes of communication
- Support for awareness

5.4 Empirical Studies of Collaborative Design

Empirical research into collaborative design is a relatively new but growing field. There is a research history of collaborative processes in the engineering domain as well as a history of conceptual design research. However, collaborative conceptual design has relatively recently become an important issue in design research. The conceptual phase of design is a challenging task to implement in a computer mediated environment because of the difficulty in sharing the design representations in participants' minds, whether they are members of same or different professions. Hence, the research on conceptual collaborative design processes has focussed on representations, communication and effects of different media on the former two. This section reviews empirical studies on collaborative processes in the architectural, product and engineering design domains.

Cross and Cross (1994) describe studies of teams of designers. In these studies, roles and relationships, planning and acting, information gathering and sharing, problem analysing and understanding, concept development and adoption, conflict avoidance and resolution provide the basis for observing teams of designers. Planning the design activity seems to be a common procedure followed by designers working alone or inside a team. Changes can be seen quantitatively in the amount of information gathered. In team design, the circulation and sharing of ideas is more substantial. In a single designer brainstorming activity, the same person formulates questions and gives answers concerning different aspects of the problem, from aesthetics to functionality.

Differing design behaviour in teams has been observed and the behaviour and performance of the individual compared to that of a team. The Delft Protocols Workshop conducted in the Faculty of Industrial Design Engineering at Delft University of Technology is an important reference work for comparing the diverse approaches to empirical research based on protocol analysis (Ericsson and Simon, 1984). An international and distinguished group of design researchers analyzed the video-recorded sessions of an individual's and a group's design activity. Different analysis approaches were adopted which made possible an analysis of the strengths and weaknesses of the design inquiry techniques and validated protocol analysis as a research technique (Cross et al, 1996). Differing design behaviour in teams has been observed and the behaviour and performance of the individual compared to that of a team. The Delft Protocols Workshop conducted in the Faculty of Industrial Design Engineering at Delft University of Technology is an important reference work for comparing the diverse approaches to empirical research based on protocol analysis (Ericsson and Simon, 1984). An international and distinguished group of design researchers analyzed the video-recorded sessions of an individual's and a group's design activity. Different analysis approaches were adopted which made possible an analysis of the strengths and weaknesses of the design inquiry techniques and validated protocol analysis as a research technique (Cross et al, 1996).

Valkenburg and Dorst's study (1998) of the team designing process was conducted with teams of multidisciplinary students where they work on a product development. They observed different design behaviours in teams, and proposed that the *context* a team creates is very important in the design process. This may go some way towards explaining why in engineering oriented design professions, it is more common to generate ideas within a group of colleagues, as in a brainstorming session. However in architectural design, the conceptual phase has largely been one person's responsibility because of a perceived notion that the contribution of several minds would not necessarily lead to an effective end result. Starting with this idea, Goldschmidt (1994) compared the behaviour and performance of the individual to that of a team[1] by analysing the processes of design thinking. Analysing the think-aloud protocols of a single product designer and team of product designers working on the same problem, she found out that the individual designer acts like a unitary system that resembles the team. However, the same results might not hold when the design process of an architect and a team of architects are analysed.

The study has two implications regarding the interaction of a team in a collaborative process:

- When a team acts together implicit or explicit roles are created for the team members, along disciplinary or behavioural lines.
- Each designer in a team develops an expertise so that strongest capabilities of each individual contribute towards the best results.

Collaborative design often takes place when the participants are in geographically distant locations. In that case, computer mediation brings about an opportunity for new forms of communication, shared views and understandings and the opportunity to design together when face-to-face work is not possible.

There has been a long history of research into the role and applications of computer media in collaborations, under terms of computer supported cooperative works (CSCW) computer mediated collaborative design (CMCD) or groupware. The computer mediation is found to have impacts on the collaborative processes; so social processes, human cognitive factors and effectiveness of communication channels have been explored through the empirical works on collaborative processes. The common issues searched in the collaborative process are investigating communicative acts of the participants in different communication channels, analysing the components of collective thinking and team behaviour and analysing social behaviours like sense of community, open participation, level of participants' awareness in the computer media and so on (Grudin & Poltrock, 1997).

One of the early studies is the ROCOCO project (Scrivener et al., 1992) cited in Mazijoglou et al, 1996) which investigated the communication channel usage of geographically separated product designers. Four different conditions of communication channels were studied. For each condition, designers were observed to adapt themselves rapidly to the changing communication types. As a result no effects of different communication channels were found. Another similar experiment was conducted by Vera et al. (1998) with architectural students in order to investigate the effect of use of two different bandwidth communication channels (audio/video versus chat line only). The change in communication bandwidth had no effect on the outcome such that the quality of the final design solution and the performance of the collaborating designers were similar in both cases. This result was based on the analysis of collaborative process actions which included the planning of the tasks: i.e. meta-planning, negotiation, and evaluation.

Based on the same study, Kvan and Candy (2000) analysed high level design communications (involving strategic design decisions) and low level ones (no strategic role) within the two different bandwidth channels. The low-level design communications were cut down in the chat-line while high-level communications were kept at the same level. The first implication is that designers adapted themselves without a trade-off in terms of design communication (corroborating the result of Mazijoglou et al., 1996) and the second implication is that text based communication (chat-line) compared to audio/video

[1] A comparative study of designing alone or in a team has been made by Günter et al. (1996) using a three phases process of analysis: clarification of the task, searching for concepts and fixing the concept. Another comparative study is reported in Dwarakanath and Blessing (1996). Often, the working alone issue is presented as an action of a single composed team (Dwarakanat and Blessing, 1996; Goldschmidt, 1994).

communication, encouraged the exploration and learning of design more effectively. Similar results have been obtained with students from different disciplines as well (Kvan and Candy, 2000), suggesting that the effect was mainly due to bandwidth of the environment not the knowledge domain of the subjects. A further CMCD study presented in the same paper describes some advantages of textual expression over the depictive expression. A conclusion was that "textual expression of early design ideas encourages exploration of underlying issues" (Kvan and Candy, 2000, p.437).

A study by Gabriel and Maher (1999) looked at pairs of designers collaborating face to face, using video conferencing, and using a chat-based virtual world. Their studies looked specifically at the communication content rather than the quality of the design product. The results show that the video conferencing collaboration was more similar to the face-to-face collaboration than the virtual world. They also found that the introduction of new ideas was significantly higher in a chat-based virtual world collaborative environment than in face-to-face or video conferencing. This study indicates that the different communication channels may have an impact on the style of communication.

Cognitive aspects of design and sketching activity have been systematically explored relatively recently with the retrospective protocol analysis method in the serial studies of design protocols (Suwa, Gero, and Purcell, 1998, 1999, 2000; Kavakli and Gero, 2001a, 2001b, 2002). These studies are mainly concerned with individual rather than collaborative design work. Munkvold includes a number of case studies of the introduction and use of collaboration technologies in the workplace and in research environments. However, this is a relatively new contribution to the study of collaborative design and there is yet much to be done in this area (Munkvold, 2003). In particular, design as it happens on the ground, as distinct from management level organisational studies, remains poorly represented.

Ethnographic empirical methods

Ethnography being a broad approach to social inquiry provides an informal mode of description and analysis. Ethnographic studies in design have been used for the purpose of making designers sensitive to the sociality of work and identify broader issues for an effective design. Some practical strategies have been defined for the use of ethnography in design (Crabtree, 2003): so called 'quick and dirty' ethnographic studies, as to provide a broad understanding of the work domain (division of labour, work activities etc.) in a relatively short period of time; concurrent ethnography, a parallel process in which investigation of work and systems design proceed at the same time; evaluative ethnography, a more focused version of quick and dirty ethnography to provide a 'sanity check' of design proposals or an existing prototype.

The ethnographer is required to bring awareness to the cooperative aspects of work revealing how work is organized by parties to the work, and whether those parties be co-located or distributed across space and time. As Saphiro (1993) puts it, "(the) ethnographic work analyst should identify particular aspects of 'what is really going on' in a given field of work and 'what is really the problem' that people encounter doing it". Ethnography's role is thus defined as to 'impart knowledge' as to the cooperative work of intended users, not to 'give form' to potential design solutions supporting that work (Plowman, 1995).

Ethnographic studies begin with exploration and inspection driven by the work under study (Crabtree, 2003). Exploration involves developing a familiarity with the cooperative work. The researcher might engage direct observation of the work or might be rather distant, observing interactions on video or listen to talk on audiotapes. Other methods include informal interviews with staff, group discussions conducted, work diaries and records be consulted. Thus, exploration aims at gaining first hand knowledge of the work of the site. Over the course of exploration, certain activities and work practices become more apparent, and some themes begin to emerge. In the inspection phase, the researcher tries to understand and analyse those emergent categories (Crabtree, 2003).

In a design context, ethnographic work is often characterized by gathering of the worksite materials; sketches, diagrams, and photographs of spaces/places, arrangement of tools/instruments/technologies and videotapes of the site's staff in action. In addition to collecting worksite material, the flow of conversation and workplace chat should be recorded and transcribed at a later stage, forming an important part of ethnographic record. Video recordings of the work environment in combination with textual descriptions could portray the sense of the real-time organization of the work, which is an essential source of data for the researcher. The analysis stage involves the production of data and extraction of findings from the records. A classification scheme is often used for interpreting the data. Classification schemes are provided by the categories that make up analytic generic formats. These categories are then used to code the data. This method of analysis, called protocol analysis, has a long history in anthropology and social science research.

Co-operative work is performed in the context of a group or team. Group-ness is conceived as a multi-dimensional variable, and the following characteristics have been used to define the group-ness variable (cited from Andriessen, 2002):

- Interdependence of goal and task performance
- Intensity of interaction
- The duration of interaction
- Formality of team membership
- Continuity of team membership
- Number of people involved

The definition of group or teamwork involves types of interaction and the social structure of the group. Social organization and the task structure become the critical subjects in the analysis of cooperative work. Thus, analysing cooperative work requires codification of workaday activities that identify the social organization of work. The task structure organizing the work may be extracted by considering the above criteria. The researcher analyses the work practices and achieves an understanding or knowledge of workaday activities. Coding instructions are applied to the record of the observed activities, and then coded results are taken to reflect the actual social/team organization of workaday activities. Similarly, coding schemes used in the design context are taken to reflect an aspect of the design process. The codes are constructed on the basis that they represent the acts, actions and activities of the human beings in the context.

A short review of activity theory and its relation to cognitive processes of the human being is given in the following section. The review clarifies the various types of coding schemes that may be used.

Action/Activity Theory and Cognitive Processes

Cognitive processes can be defined in terms of human actions. Using certain tools and performing a work can be defined as a form of human action. Three mechanisms have been distinguished which regulate people’s behaviour when trying to perform a certain task (Andriessen, 2002 p 57):

- The action mechanism, which regulates the goal-directed activities (perception, memorising, information processing, decision making etc.)
- The capacity mechanism mobilises and allocates resources, where the focus is on psychic energy, on arousal, effort and activation
- The self-evaluation mechanism cares for the maintenance of a positive self image.

Activity theory as formulated by Leont'ev (1981) and expanded by Engeström (1987) is a comprehensive theory concerning human social interaction with tools, in the context of a community. The theory also develops a rich idea of *context* in which the human actions take place incorporating social construction of norms and artefacts. Activity theory has recently received attention within the communities of human-computer interaction and computer-supported co-operative work (CSCW). Activity theory places a systematic, formal emphasis on identifying roles, actors, and communities relevant to a project and, very critically, an understanding of conflicts and tensions in the intended activity early in the design process (Redmiles, 2002).

As a number of recent publications show (Beach, 1999; Engeström, Miettinen and Punamaki, 1999;Nardi, 1996) Activity Theory is proving a useful tool for analyzing and theorizing about workplace activity settings, in which it is relatively easy to identify material objects that subjects transform through the use of artifacts of various kinds.

The primary concept employed by Activity Theory (AT) is human activity. Activities, as defined by AT, provide enough contextual information to make an analysis meaningful, while avoiding a narrow focus on an individual or too broad a focus on whole social systems (Kuutti and Arvonen, 1992). Similarly In cognitive psychology, action theory is defined focusing on purposeful human (individual) actions: The basic assumption of the theory is that work is a goal directed activity. The objective goal or task given to a person in a situation is always interpreted by the person and translated into a subjective perceived goal/task (Andriessen, 2002).

In activity theory the unit of analysis is an activity that is being composed of subject, object, actions, and operation. A subject is a person or a group engaged in an activity. An object is help by the subject and motivates activity. 'Behind the object there always stands a need or a desire, to which [the activity] always answer.' Thus, action theory makes distinction between acts, actions and operations. Acts are complex sets of actions, aimed at realising intended goals. Actions are the smallest independent units of cognitive and sensory motor processes that are still oriented towards conscious goals. Operations are components of actions without independent goals. Central to AT is the concept of mediation by which is meant the relationship between subject, object and community as mediated by tools, rules and division of labour. These artefacts are used by a community to achieve a desired set of transformations on an object. Artefacts can range from physical tools, like a hammer, to psychological ones (Bardram, 1998).

Situated Action Theory (SAT, Suchman, 1987) is defined as the concrete activities of people in specific settings. According to this theory, researchers should also direct their attention to the situational determinants of individual action, to behaviour as a response to the environment and to the improvisational nature of human activities. Thus SAT could be considered as an approach to analysing the "situatedness" of behaviour, and analysis of unstructured tasks and free behaviour.

5.5 Key Issues in Collaborative Design

There are many studies that reveal the nature of design thinking and the characteristics of early conceptual design as distinct from detailed or embodiment design. The results of those studies can assist in our understanding of how the process of design can be supported and how new technologies can be introduced into the workplace (Munkvold, 2003). Most studies, however, provide limited information about the nature of collaborative design as it takes place on the ground and in the actual working context. The provision of support for collaborative design information sharing for across companies, countries and heterogeneous computer systems is a key issue. As data are passed between designers and the computer systems they employ, many exchanges of data are made. These exchanges may be used to establish measures of the benefits that new support systems can bring (Britton et al, 2001). The data that are exchanged, whether it takes the form of paper drawings, phone calls or faxes or computer based designs, must be taken account of in the transition towards more complex collaboration technologies. Indeed, without an understanding of the nature of existing collaborative design practices, as well as the role that materials and tools play, it is difficult to arrive at an understanding of designers' needs in relation to new technologies. The nature of collaborative design thinking is different to that of individual design thinking and requires attention to all the elements that impinge upon the process from the human cognitive capabilities to the social and organisational contexts. For that reason, empirical studies that employ methods for revealing the rich and complex picture of collaborative design are needed.

6. COLLABORATION TECHNOLOGIES

Collaboration technologies may be classified according to the communication tasks and knowledge sharing activities that are undertaken using electronic systems support for example:

- Communication: e.g. email, instant messaging, audio/video conferencing
- Shared Information: e.g. document management systems, electronic bulletin boards
- Meeting Support: e.g. electronic meeting systems
- Coordination: e.g. calendar and scheduling systems
- Integrated Products: e.g. e-learning, team support suites (Munkvold, 2003)

These technologies are a familiar part of today's commercial and educational environments, although it is not unreasonable to say that their use may often be ineffective for a variety of reasons. Not all organisational environments that require communication and meeting activities have the necessary infrastructure, network bandwidth and digital tools to meet the specific needs of complex professional tasks and it is in architecture and construction that some of the major challenges for collaboration technologies are to be found. Stand alone systems such as AutoCAD are in routine use in many companies but what is not readily available is the technology for simultaneously sharing drawings, images and models amongst any number of participating users in flexible, high performance virtual design spaces. Such spaces, where users can freely create, modify and evaluate designs in common with full awareness of other users' presence and actions are not yet widely in serious use. Half way measures that allow users to see one another's actions on a shared electronic drawing board and respond with similar actions do exist but, as yet, in limited formats. The exact replication of the face to face design activity in all its richness has proved to be harder to achieve than first imagined and, in any case, the emphasis has moved away from aiming for such replication (often a degraded experience for the designers compared to the conventional physical tools). The aim now is to identify and provide value added elements that do not simulate the design tasks but rather extend the range of possibilities in other directions: for example, being able to share knowledge relevant to specific tasks. In the case of building design a significant form for information representation is the 3D model.

Thus, there is an additional type of collaboration system, that of the shared 3D model. Support for this should be included in an integrated product for professional design, as per the above classifications. For the architectural and construction industry, such support could be found in an integrated design and collaboration environment which supports the multiple views of a team in the exploration and investigation of the form and structure of a build environment to arrive at a shared understanding of the solution.

The following sections outline three types of technology significant for this review:

- Domain specific tools for conceptual design tasks. These are concerned with extending computer support in design within the conceptual design phase but do not necessarily address collaboration.
- General-purpose collaboration systems for communication and knowledge sharing tasks. These are concerned with human-to-human collaboration through or with digital technology but do not specifically support design tasks.
- Collaboration environments for 3D modelling and multi-user participation. These technological systems are specifically concerned with the support of collaboration through or with digital technology within design tasks.

6.1 Conceptual Design Tools

Qin argues that traditional CAD systems do not readily support the conceptual design process since these systems usually require complete, concrete and precise definitions of the geometry which are only available at the end of the conceptual design process or later. Moreover CAD applications tend to be optimised for the creation and manipulation of geometry rather than spatial creation and the manipulation of imagery. This only allows limited visualisation of the objects being created and only from a static point of view when the designers are performing highly integrative act creating a physical presence.

Some of the limitations of the traditional CAD systems defined by Qin (Qin et al, 2003) include:

- Limited viewing angle and resolution of a typical workstation screen which confines the space being designed. This leads to a shift in focus from inhabitable space to external form.

- Design of the space can be negatively influenced by the shape of the screen and by its horizontal and vertical edges.
- CAD tends to be optimised for creation and manipulation of geometry rather than spatial creation and the manipulation of imagery.
- Limited visualisation when creating a physical presence of objects.

The above limitations can be overcome in many different ways (see e.g. Anderson et al, 2003, Bajaj et al, 1999, Leigh et al, 1999). Some of these approaches are now described. From the detailed protocol study into how designers work during conceptual design with emphasis on how information is manipulated and organised, Meniru has identified a set of specifications for any computer system built to support conceptual design building (Meniru et al, 2003). The specifications outline some of the functionalities that are desirable in systems that support conceptual design in terms of data representation, manipulation, and display. For further details about the systems identified please refer to the project research report (Yoon, J.S. 2003).

A number of tools that have been developed to facilitate conceptual design have been identified. They each support different aspects of conceptual design. No single system provides a complete repertoire of functions that support all requirements for collaborative distributed design. Many depend on idea or solution exploration by allowing designers to quickly sketch ideas and analysing them. Some depend on exploring previous solutions to adapt to new design problems. Two examples are:

Sketchup

SketchUp is a single user tool for exploring early design ideas. It enables the creation of 3D forms, which can be modified in a readily accessible form. It can exchange data with all standard CAD, 3D modelling, image editing, and illustration applications. The lack of multi-user capability, restricted asynchronous communications and no facility to add, store and retrieve verbal annotations are the main limitations of this tool. http://www.sketchup.com/

Solidworks

Solidworks is a tool that provides feature-based 3D modelling capability for mechanical design. It comprises basic part modelling, assembly composition and from that drawing creation. There are considerable limitations to the capability of this tool as it stands to support collaborative design: it is single user system with no synchronous communications. It also has restricted design annotation facilities. http://www.solidworks.com/

6.2 Collaboration Support Systems

In the construction industry in the early stages of design, various disciplines collaborate in producing possible solutions that satisfy all participants' needs. There arises, therefore, a need for distributed collaboration since these collaborators may either be co-located or be in various locations. The following media have been utilised in the industry in order to support collaborative conceptual design activities:

- Audio and Video Teleconferencing
- Speaker phones
- Electronic Mail

These media are valuable components of distributed collaboration but they do not address the important facility of enabling each participant to simultaneously create, modify, annotate and view a shared 3D model with other designers in the team.

For real-time collaboration among designers the following issues need to be considered (Fenves, 2000):

- Concurrent data access
- Synchronous and Asynchronous communication
- Conflict Resolution Strategies
- Data Ownership
- Data Distribution

A number of systems both research prototypes and commercial products have been identified. The following sections summarise the main systems that could be considered as candidates for supporting the kinds of team collaboration envisaged in the project domain of concern and also to support a set of collaborative design tasks. Concept design support tools such as NetDraw, Sketchup, SolidWorks, VR Sketchpad, Architecture AutoDesk, Space Pen, are being evaluated against an agreed product description, including user requirements, and a set of features that support a range of design activities, interaction and meeting modes and system specifications.

The following general-purpose tools provide various forms of collaboration support: communication, meeting support, shared drawing:

iStorm

iStorm is a collaboration system that provides a range of facilities including a shared whiteboard (chalkboard), voice and picture messaging. It has particular features that are valuable to collaborative science, e.g. TeX and mathematical facilities but is not aimed specifically at design. In MacOSX, it can be used in conjunction with Apple's iChat AV to provide both full video conferencing and shared sketching.

http://www.mathgamehouse.com/istorm and http://www.apple.com/ichat/

TeamSpace

TeamSpace is a web-based collaborative workspace system developed by IBM and The Boeing Company to support spatially distributed teamwork. It integrates inherently synchronous technologies such as audio, video, and data conferencing with real-time awareness and asynchronous technologies to support articulation work. http://www.research.ibm.com/teamspace/

PortfolioWall

PortfolioWall is a collaborative environment designed to work with touch-screen systems which enables teams to view, share annotate, manage and make decisions about visual objects. PortfolioWall is designed to be used in locations away from the desktop and is intended to act as an umbrella technology that links to a variety of other software http://www.aliaswavefront.com

Other collaborative conceptual modelling tools in the design field also suggest creation, manipulation and viewing 3D models in a shared virtual space. Netsketch, for example, which is collaborative conceptual 3D modelling tool (LaViola et al, 1998) suggests a fast and gesture-based user interface (for the drawing communication -the SKETCH gesture metaphor (Zeleznik, 1996), a set of visual effects that enable a user's awareness of operations done by other participants and a set of tools for enhancing visual communication between participants.

6.3 Collaborative Virtual Environments

Some computer-based systems offer a new range of collaborative experiences. Collaborative Virtual Environments (CVEs) provide distributed spaces where people can interact with others, with agents or with virtual objects. This section describes some of these virtual environments and how they can augment the collaborative design process. There have a number of limitations that need to be addressed before they can be considered adequate for the professional working environment.

A Collaborative Virtual Environment (CVE) is a computer-based, distributed, virtual space or set of places. In such places, people can meet and interact with others, with agents or with virtual objects. CVEs might vary in their representational richness from 3D graphical spaces, 2.5D and 2D environments, to text-based environments.

The key features that a CVE is able to support are:

- shared context
- awareness of others
- negotiation and communication
- flexible and multiple viewpoints

A "shared context" can mean shared knowledge of each other's current activities, shared knowledge of others' past activities, shared artefacts and shared environment.

"Some technologies, such as 3D virtual environments, are inherently spatial, and it could be argued that some 3D virtual environments suffer because they depend too much on space without supporting the creation of a sense of place. CVEs need to support the evolution of places for interaction, and not simply provide spaces where interaction can take place, if they are to be successful in the long term" (Snowdon et al, 2001, p8).

Many computer technologies that have been developed to facilitate collaborative design enable designers to sketch ideas and analyse them. Some depend on exploring previous solutions to adapt to new design problems. Media that have been used to support collaborative activities include audio, video and tele-conferencing, speaker phones, and electronic mail. These media are valuable components of distributed collaboration but they do not address the important requirement to enable each participant to create, modify, annotate and view a shared 3D model simultaneously with other designers in distributed locations.

In a study about conceptual design for assembly of the parts in mechanical engineering, Lombeyda and Regli propose a set of basic requirements to support conceptual design in a collaborative environment:

- CAD capabilities for creation of designs and object primitives with embedded S-Behaviour-Function characteristics.
- VR environment, to explore the design, for collaborative interaction and work.
- Communication protocols, to create a multi-user environments
- Portability/interoperability give the designer opportunity to work on any platform (Lombeyda and Regli, 1999)

The same study describes a 3D sketch environment in which designers create a 3D “freehand” sketch and the general structure of the artefact without detailed CAD. The authors develop a 3D modelling approach to conceptual design that enables teams of designers to embed semantic (S-B-F) information in their models[1]. In the same study they propose a virtual environment platform where users will have the ability to participate in a shared workspace, as well as make use of a personal workbench or white board. When participating in a shared workspace it is assumed that a parallel system of communication is also being used (text chat, web phone, etc.), but at the same time users interact in the design space, viewing the design at work, as well as being able to see the other users present in the world through their avatars. As users interact, they are able to create, modify, and even destroy objects within the design, following a protocol where objects may be requested, relinquished in control, or even protected or hidden from other users.

The claim for virtual environments to support remote collaboration is that they offer the following advantages:

- The ability to present a large amount of information
- Natural information lensing
- Support for many sensory modalities
- Natural multi-user interaction
- Natural awareness of co-workers' activities

TeamSpace (Fuchs, Poltrock and Wetzel, 2001) is a collaborative workspace (for geographically distributed teams) to support individual, social and meeting work modes, and facilitating the transitions between these modes. Individual mode refers to work alone with specific tools of the discipline, and this work is defined as the ‘real work’. Then all members gather in a meeting room at scheduled times for work, which is referred to as meeting mode. Social mode refers to meeting of two or more people for talking informally. The communication modes for TeamSpace could be synchronous (instant messaging, IP based voice and video conferencing) or asynchronous (email, bulletin board, etc.). There is another categorization in the TeamSpace framework for the tasks present in the platform. Those three categories are work related tasks, meeting related or people related tasks. The role of awareness for team performance has also been emphasized in the TeamSpace framework, with synchronous and asynchronous awareness mechanisms.

Wang et al. (2002) summarize two approaches to collaborative conceptual design: web-based and agent based. In the web-based approach, the Internet is used by the design team members as a collaboration tool, for access to catalogue and design information of the product/design, for communication among multidisciplinary team members, and for access to design tools, services and documents. In the second approach (Wang et al., 2002) to collaborative conceptual design, agent technology is used, where a network of problem solvers work together to solve problems which are beyond their individual capacities. Agents in such systems are supposed to be communicative, collaborative, autonomous, reactive and intelligent. Considering agent theory Brazier et al. (2001) have modelled the knowledge-level of an individual designer as an agent. This model, which is based on existing models of single agent design, is illustrated with an individual designer in a specific distributed design process. The paper explains the agent-based approaches to collaborative conceptual design and summarizes the research on distributed design, single agent-multi agent systems. Key issues, such as agent/designer's reasoning about a situation and agent/designer's interactions within the design environment, are highlighted.

Recently Qin et al. (2002) described a system where the designers first sketch their conceptual design and transform the design into a simulation model (from 2D to 3D), then send or broadcast the animated simulation model of the conceptual design over the internet to enable collaborative working with designers, manufacturers, clients etc. who wish to evaluate/verify the initial design ideas. They have used a VRML based simulation to let the designers publish their work on the Internet, so that non-expert users and non-CAD users have easy access to the 3D design model in order to explore the model in dynamic simulation form.

When using virtual environments particular requirements need to be met (Anderson et al, 2003). These include having:

- Avatars that can convey non-verbal information such as body language and gesture,
- Suitable interfaces for collaborative manipulation and visualisation to allow collaborative manipulation of shared objects,
- Audio/Video Teleconferencing as audio still plays a vital role and video provides sense of co-presence but with the use of avatars may decrease the role of video conferencing in the collaboration,
- Flexible support of various data characteristics,
- Scalable and flexible topological construction for virtual environments,
- Synchronous and Asynchronous collaboration as it is necessary when trans-global collaborations are needed,
- Persistence in collaborative virtual reality,
- Interoperability with heterogenous systems,
- Application specific servers that are needed for a local representation of the virtual space.

A selection of key CVEs is presented below.

ActiveWorlds

Active Worlds adopts a 3D immersive design approach. The ActiveWorlds virtual environment simulates the real world and allows its 'citizens' to design implement and extend the environment with an emphasis on community design http://www.activeworlds.com

NetSketch

NetSketch (LaVoila et al, 1998) is a 3D design tool allowing small groups of remote collaborators to simultaneously interact with a virtual shared 3D model. It uses visualisation techniques that allow designers to identify and resolve contentions about objects. NetSketch provides a range of group interactions that encourage direct communication between individuals for the purposes of feature highlighting, model annotation and attention focusing. To allow designers to be aware of others using the environment, NetSketch uses ambient environmental cues which are perceived when the user's threshold for distraction becomes low enough.

The interface for the system uses a gestural interaction metaphor based on the Sketch system developed by the same researchers. It allows users to directly perform the intended tasks and operations. This increases the interaction speed as well as helps designers to keep their focus on the design session while constantly being made aware of what others are doing in the design environment.

NetSketch utilises a 3-button mouse that designers use to draw lines on the image plane of a 3D view which the system interprets as geometric operations and primitives. This method of manipulation limits the functionality of NetSketch and also limits the precision of the operations possible. However, it is the researchers' belief that these shortcomings are tolerable in collaborative environments where the most critical issue is that communication bandwidth be maximised. NetSketch, in their point of view, does maximise the communication bandwidth through hand gestures and scribbled drawings.

Visual ambient cues in NetSketch are used when an object in a shared world is either created or deleted. These visual effects include fade in and fade out effects used to signify creation and deletion, respectively, of objects. Another effect tested by the researchers is of scaling of objects. These effects are employed overtime to smooth the jarring motion of objects that pop in or pop out of existence in the virtual environment. To display the objects that have been moved, the system utilises a ghostlike transparency copy of the given object that moves in the direction of the real object. After a short interval, the transparent copy will appear and follow the real object. Another visual effect is to use streaks of lines from the initial position of the object to where the object gets placed.

Handling differences about objects is vital in any collaborative modelling system: in NetSketch, when a conflict is detected, multiple copies of the same object are created for use by the individual designer. The last change made to the shared object is displayed overall and the system delegates it to the designers to come to a decision as to which modification is to be agreed upon.

NetSketch allows designers to share viewpoints when necessary. This is made possible by designers invoking a command – simply by hitting a shortcut button – that creates a magic lens on the screen of the other users. These viewing lenses can also be used to present a zoomed in viewpoint by drawing a lasso around the area of interest and invoking the view lens.

There are two mechanisms for annotations in NetSketch:

- View Lens – used to make 2D drawings allowing designers to describe and annotate parts of the 3D model using another designer's viewpoint.
- Annotation Arrow – the system creates a 3D arrow in the virtual environment when a arrow-like sketch is made in 2D. These arrows can be moved around and will always snap to the normal of a given face of an object. This method allows designers to indicate a particular feature from any viewpoint unlike the method that utilises view lens.

This system is a prototype and as such still suffers from many limitations. NetSketch is based on peer-to-peer topology. It is built to be a tool for creating, manipulating, viewing, and annotating 3D models in a shared virtual space. The prototype system provides the designer with a fast and direct gesture based interface for rapid creation and discussion of 3D models.

VR Sketchpad

Unlike NetSketch which does not interpret freehand drawings, the VR Sketchpad system (Do, 2001) interprets the freehand drawings and uses these drawings in creating prototype 3D virtual scenes. This allows designers to generate 3D worlds based on sketch diagrams for spatial partitions such as walls, columns, and furniture on a 2D floor plan. This enables the designers to experience a virtual walkthrough using a web browser capable of viewing VRML files. VR Sketchpad allows designers to create their own graphic symbols and gestures by drawing examples into the system using input devices such as a pen and a tablet. These symbol libraries are personalised to each designer which the system then provides meaning association and performs geometry translations.

Using these symbol libraries the designers then simply draw sketches to indicate the placements of items. The colours for these items can be specified by the designers. VR Sketchpad uses this information with the sketch drawing to create 3D world accordingly. The contexts in which this system can be used depend on the personalised libraries. Some of the designs that are possible on this system include architectural space, and furniture layout. Even with the same set of sketches, it is possible to create different types of 3D worlds since the same symbol may represent different items depending on the context. For example, a circle drawn can represent a column in the case of floor plan designs, or it can represent a table in the case of furniture layout designs.

There are three types of interfaces available in VR Sketchpad for the sketching input:

- Regular Drawing Board – displays sketches as drawn.
- Picture Underlay with Multiple Translucent Layers – trace layers are overlaid on top to add modifications and annotation diagrams. Each layer has a corresponding tag to allow easy management of different trace layers.

- Transparent Window – maintains the drawing functionality of the previous two types of interface. This window displays the screen's pixel map as a background for its contents.

Gesture recognition is also supported in VR Sketchpad which enables a designer to specify viewpoints in the 3D VRML scene. Using a sequence of viewpoints a viewing path into the 3D world can be defined. The prototype system is developed to illustrate the relationship between 2D and 3D. Although the system is not developed specifically for conceptual design, it can be used to generate ideas as well as visualising the ideas for further analysis. This system, however, is not developed to be used as a collaborative design tool, although an asynchronous collaboration is possible by publishing a VRML scene, which is to be analysed, on the internet for other collaborators to give feedback. Currently the researchers are planning to extend the functionality of VR Sketchpad including features that allow designers to specify the heights of items being drawn.

SEED-Config

A prototype system has been built as a part of SEED (Software Environment to support the Early phases in building Design) to provide computer support for the preliminary design of buildings (Fenves, 2000). The intent is to assist designers in generating designs, not to generate design automatically hence the emphasis is on supporting early design exploration, that is, the fast generation of alternative design concepts and their rapid evaluation against a broad spectrum of relevant, and possibly conflicting, criteria.

The system is built based on the Object Oriented application framework ET++. It is written in C++ and compiled in GNU Unix environment on DEC Alpha computers. The SEED system is subdivided into a collection of modules, and the three main modules are SEED-Pro – for the generation of architectural programs, SEED-Layout – for the generation of schematic layouts, and SEED-Config – for the generation of 3D configurations of spatial and physical building components.

The prototype of SEED-Config has features that support multiple views, conceptual design exploration, and customisation which are not readily found in conventional CAD packages. The prototype supports conceptual design exploration as it allows each design problem to be decomposed into the most detailed entities forming a hierarchical structure of design abstractions. Any given building entity can be classified as pertaining to more than one design domain and can accumulate components of interest to different designers, to be shared across multiple views. Furthermore, the building decomposition hierarchy may contain the decomposition of several building systems side by side. Hence, the decomposition of the enclosure system may exist beside the one for the structural system.

The prototype system is capable of being customised. This customisation is provided by two mechanisms: technology nodes which encapsulate design knowledge, and an expanding case library of design cases generated as a natural by-product of the design process. Moreover, designers can incorporate support for their own style by augmenting or modifying conceptual models, classifications, and technology nodes independently. The system offers three different design methods: interactive design using technology nodes, case-based design, and manual design. This makes backtracking possible when performing conceptual design exploration to return to prior decision node.

Limitations of this prototype system include:

- Lack of commercial geometric modelling which can model sloping, curving and non-orthogonal geometries,
- Lack of support for real-time collaboration among designers,
- Lack of repository or brokerage of technology nodes, shared by the entire profession,
- Lack of an intuitive user interface.

These limits need to be addressed to convert a laboratory prototype, built as a proof-of-concept and to explore ideas, into a practical tool for designers.

A Framework of Web-Based Conceptual Design

A prototype system has been built to investigate sketch and simulation based design tools that allow designers to model their design ideas quickly and test their design by products' behavioural simulation on the Internet (Qin et al, 2003). This helps during conceptual design phase when each design is quickly modelled and assessed. The system supports collaboration during this stage by broadcasting simulation models to designers, manufacturers, and customers. The system has two main components: a geometric modelling component and a behavioural modelling component. The geometric models are created from sketches made by designers. The system has a sketch interpretation system which receives its inputs from a conventional mouse. While sketching, the system gets a sequence of input data from mouse button presses, mouse motion and mouse button release events. This sequence of data represents a freehand curve that may consist of several sub-curves. This sequence of data is then segmented into meaningful parts according to sketching position, changes of drawing direction, drawing speed and acceleration. After segmentation, each sub-curve is represented by a corresponding 2D primitive which is then fitted with corresponding parameters. These 2D entities are then roughly placed at their proper positions and directions which may not reflect the designer's original intent. A geometric constraint inference engine and a constraint solver are utilised to capture the designer's intention, and to generate a possible solution. When enough 2D geometry is accumulated, 3D feature sets can be built which can be examined by the designer as a wire-frame model or as a shaded solid model from different views. An alternative method to sketching is to input 2D primitives interactively giving more control and freedom in inputting 2D information. The current prototype only supports extruded objects.

CUP Conceptual Understanding and Prototyping

CUP (Regli, 1999 was developed to support computer-aided conceptual design of mechatronic assemblies in a collaborative, multi- user environment. It allows a team of design engineers to collaboratively develop a high level Function-Behaviour-Structure (FBS) description of an assembly in a VRML based virtual environment over the internet. CUP enables users to perform design at conceptual level by navigating Product Data Management (PDM) and case-based design knowledge bases. It also has intelligent CAD tools that can draw on details from repositories of previously archived designs.

CUP is:

- CAD-based – designers require basic CAD capabilities to create designs, primitives, and embedding FBS characteristics.
- VRML environment – to provide an environment for collaborative interaction and work.
- Communication – to create a multi-user environment.

CUP allows a designer to quickly sketch out the major components and structural relationships in the assembly. This helps designers to quickly build a conceptual design. This design then can be used as a starting point for further refinement or as a query to the design knowledge-based. CUP helps designers to capture the essence of design intent and to build a model of the artefact.

OneSpace Collaboration

OneSpace Collaboration software is a collaborative virtual environment with features support viewing and modifying 3D models. http://www.cocreate.com It provides the following functions:

- View, inspect and modify 3D models
- View and share documents and drawings
- Mark up data
- Make and document decisions
- Manage meetings
- Integrate into PDM (Product Data Management) systems

6.4 Key Issues for Collaboration Technologies

Technologies to support communication and design have been developed in different fields of research and, as a result, the tools that have arisen are not as yet tailored for the domain of interest, that of design, architecture and construction. Attention to collaboration technologies specifically for design is to be found in centres such as the Design Machine Group in the Faculty of Architecture at the University of Washington, USA (DMG, 2003). A focus on advanced collaboration technologies using VR/3D modelling techniques may be found at the Communications Research Group at Nottingham University, UK where research into the use of computer and communications technologies including Collaborative Virtual Environments (CVE) is undertaken (CRC, 2003). In both cases, the tools for collaboration that have been developed are research prototypes and, whilst useful for testing and evaluation in laboratory settings, would not meet the requirements of a real world design office.

A number of research and commercial tools that have been developed to facilitate collaborative conceptual design were identified in this survey. They each support different aspects of conceptual design. No single system provides a complete repertoire of functions that support all requirements for collaborative distributed design. Many depend on idea or solution exploration by allowing designers to quickly sketch ideas and analysing them. Some depend on exploring previous solutions to adapt to new design problems. The systems utilising virtual environments are limited in functionality as they cannot be used to modify the models in real-time and display the result of the modifications. However, they are well suited to providing collaborative environments as well as providing information visualisation. Those systems that allow modifying of design solutions only offer limited information visualisation and do not readily provide multi-user capability. A key research goal is to find a balance between the two methods to support collaborative conceptual design for construction industry.

The commercial systems available in the market that were identified provide a number of design task support functions. It is necessary to match the functions and facilities they offer to the requirements of the industrial partners. Given an appropriate match, the selection of appropriate tools for the studies to be undertaken can be carried out. The extension of facilities and interaction methods is likely to be required. The analysis of these tools and relevant research tools is ongoing.

Marchese et al (2003) show how a single user system can be adapted to support web-based collaborative communication and data model interrogation and manipulation. The system enables collaborating users to display, transform and measure 3D objects and during the session use text chat or other communication tools for audio or video conferencing. A key issue identified was the problem of providing a shared sense of presence for all participants in the virtual space.

Another technical issue is whether to adopt a client server or Peer to Peer (P2P) networking approach. Client server constraints occur because the server needs a predefined IP address to make connections, at a time when more and more servers have dynamic addresses. The use of a protocol such as JXTA which allows any network connected device to communication and collaborate, to create a P2P network resolves the client-server constraint by interconnecting machines so that each node acts as both server and client. This promotes robustness, Marchese et al argue.

Collaboration support tools represent a fast growing section of the commercial software market place and a reasonable range of products are available. Many of them offer significant application to design for the support of distributed meetings by the provision of video and audio communications and the sharing of information, including collaborative sketching. The tools that specifically support 3D models and other very design specific features are less common and many of those are in prototype stages of development. A key question is to find viable ways of combining design information visualisation support with the collaboration support technologies that can be seen today. A significant research question is to find principled ways of migrating single user conceptual design support systems to full collaborative conceptual design environments. In such environments ways are needed to provide a shared sense of presence to the designer participants. Finally, there are technical issues still to be resolved such as the importance and applicability of P2P as against client server architectures.

7. MULTI-VIEW MODELLING

As current design projects are increasingly large and complex, involving multidisciplinary collaboration among many disciplines including architectural, engineering and construction disciplines, this raises the issue of the role of multiple views in collaborative design. Multiple views are concerned with the perception, conception and representation of design objects by different participants in a design context (Rosenman and Gero, 1996). In other words, each discipline has its own concepts and interpretations regarding the information concerned with the representation of a design object. Research into multi-view approaches include database and object oriented approaches, CAD systems, data representation and standardisation methods and system architectures (Naja, 1999).

7.1 Data-base Approaches

This approach addresses the issues of data modelling, which describe the data types, relationships and constraints of the information which is stored in a database. Taking a database viewpoint, Naja (1999) proposes the CEDAR model as an object-oriented multi-view database. Because conventionally, object models are not able to model data described from several viewpoints, the goal of the CEDAR model is to define a model allowing a multiple representation of objects, classes and schemas. The primary features of this model are multi-view objects, multi-view classes, multi-view schemas and multi-view bases.

According to Naja, the multiple representations can be characterized by the following features:

- Kernel of the multiple representations: This is often formed by properties that describe entities independently of any viewpoint and all along their existence.
- Independence between representations: Different designers can separately define their representation of an entity without any one needing to know the characteristics of this entity according to others.
- Sharing between partial representations: When defining a partial representation of an entity, a designer need to access to some information associated to the entity and defined by another designer.
- Coherence between representations: Multiple representation of a concept consists in describing it by a kernel and by several partial representations. Therefore, the local integrity of each representation and the global integrity of each representation taken together must be ensured.
- Evolution of the multiple representations: During its life, a concept does not keep the same representations, but it can undertake or relinquish numerous partial representations.

The CEDAR model manages the first four features. In order to make the modelling task easier, a system based on graphical interfaces allowing the definitions of multi-view schemas and bases has been developed. The tools provide the kernel hierarchy browser, the kernel repository browser, the viewpoint dependent hierarchy browser and the viewpoint dependent repository browser.

There is much research into the development of integrated project database for multi-disciplinary communication and information sharing in construction projects. One of these projects is the Computer Models for the Building industry in Europe (COMBINE) project supported by the EU's JOULE and Delft University of Technology. It aims to develop a computer-based integrated building design system (IBDS) by adopting an integrated project database approach. The Integrated Data Model (IDM) is being extended with a central Data Exchange System (DES). The DES is a central data repository which users from different architectural and engineering background can access and exchange data during the construction process. The integrated data model (IDM) was implemented as an object-oriented database including all building objects. The database is managed by a custom-built data exchange system using the STEP neutral data format (Sun el al, 1997). The current limitation of this system is that such exchange capabilities are only available off-line.

Similarly to OSCON and WISPER conducted at Salford, the GALLICON project provides an integrated project database approach that aims to develop an integrated design system to support project process for the design and construction of water treatment plants in a multidisciplinary project team. The prototype system consists of an integrated project database, a process manager and a suite of applications which are interfaces to four third-party AEC software packages based on the process model and the analysis of requirements of the industrial partners. The GALLICON modelling task complies with the existing IFC object model and STEP. The integrated project database is used to store not only building objects but also process objects.

According to the authors, the potential benefit of using the system is in the automation of quantities take off, cost estimating, time planning and the remote access of such information.

7.2 CAD Systems

In CAD systems, viewpoints are used to manage the multi-expert aspect of the design progress (Naja, 1999). For example, Nederveen and Tolman (1992) propose aspect models, which are represented by a NIAM (Nijssen's Information Analysis Method) diagram describing real world entities according to a particular viewpoint. The NIAM especially represents constraints on relations between entities. All aspect models are based on a kernel which store view-specific information, and each entity of an aspect model must be a sub-type of an entity of the kernel. According to Naja, this is a restriction because we need sometimes to create entities that are not linked to any entity in the kernel. Although this approach resolves the problem of a multiple representation at a conceptual level, it has a limitation in updating the model through real design processes because it defines a static-schema, which is incapable of evolution.

Rosenman and Gero (1996) present functional modelling in collaborative CAD modelling based upon an assumption that different views of an object are based on different functional contexts, where functional concerns include non-technical functions such as aesthetics, symbolism and psychological effects. The current practice in CAD systems is to present merely the structural properties of an object, usually only the graphical representation, such that the information regarding the object's intended functions is lost.

Rosenman and Wang (2001) present an open-system architecture for a collaborative CAD system supporting virtual product development. The primary feature of the system is that it adopts the mode of "distributed Components + Assembly Shop" and a component-agent approach to improve the self-maintenance capability of each component. Because designers get the information related to their discipline from a CA (Component Agent), the CAs have multi-views, which requires having both common model data and discipline model data. This multi-views modelling approach uses the paradigm of purpose-function-behaviour-structure and multiple partners use their own ASs in different places and share the same CAs.

7.3 Data Representation and Standardisation

Research into how data is represented, shared, and managed between the myriad of software applications is also relevant to this topic. The initial requirement for a standardised data model starts from the need for different CAD application to share their graphic files. The following are several projects addressing the data exchange issue, which include ISO-STEP, IAI/IFC, EXPRESS and so on. They are reviewed by Amor and Eastman (Amor,1999; Eastman, 1998).

The International Organization for Standardisation (ISO) standard for exchange of product model data (STEP) was developed in 1983. The goal of this standard, officially named ISO 10303, is to facilitate the exchange of the information of an industrial product by defining data models. STEP also defines standard methodology for data modelling and data exchange. In order to achieve software interoperability in the AEC/FM industry, the International Alliance for Interoperability (IAI) was formed in 1995. It seeks to define and publish a specification for sharing data across disciplines and technical applications. Similar to the STEP model, IAI adopted the object-oriented modelling paradigm. The IAI model is a collection of Industry Foundation Classes, (IFCs). IFCs are data elements that represent the parts of buildings, or elements of the process, and contain the relevant information about those parts. They provide a means to encode and store information for the entire project in a model that can be shared among diverse project participants.

The STEP and IAI IFC present a comprehensive conceptual model for the building system including the data requirements. However, each application uses only a subset of the model and has a partial view of the model. Data mapping standards are therefore necessary to map these data views of different software applications. In particular, the EXPRESS mapping language defines a common interpretation of the standard in terms of data and rules for STEP. Amongst a number of dialects of EXPRESS, EXPRESS-M was developed to solve the problem of application protocol interoperability in the STEP standard. It is a schema mapping language that describes how entity instances should be mapped between schemas in order to facilitate the transfer of data between models. EXPRESS-V was developed to define views of an integrated data model in EXPRESS format. It defines not only a mapping from the original information model to the view but also a mapping from the view back to the original information model (Sun et al. 2000).

CIS/2 is a CIMsteel building model which has multiple views of a steel structure developed by Leeds University (UK) and SCI (Steel Construction Institute) over ten years. It encompasses more than previous protocols for electronic data change (EDI) and allows information to be passed from the design phase to detailing, fabrication and the production of a bill of materials. By providing a neutral data format, CIS/2 allows data interchange between a wide variety of program types. Pierra et al (1998) present an overview of the PLib (officially ISO 13584, Parts Library) information model, discussing the use of PLib for the design and the use of on-line electronic catalogues. They also deal with cooperation between PLib and STEP for an integrated data management capability. The PLib specification encompasses many aspects and includes a number of EXPRESS constructs. These models enable users to structure of data which has multiple formats and also to query knowledge and information from multiple views in order to support knowledge management.

7.4 System Architectures and Environments

The web-based IFC Shared Project EnviRonment (WISPER), a collaborative working environment for construction is proposed by Faraj et al. (2000), is based on a three tier architecture including user interfaces, business logic and database. It is a distributed computer integrated environment which supports design (CAD), visualisation (VR and DWF), estimating, planning, specifications and supplier information. WISPER enables project information to be exchanged through a STEP Part 21 file and shared through the IFC database. This is a consequence of two large projects SPACE and OSCON, but has not been fully implemented by technology. Although these models propose a multi-view of a database, they just mention integrated databases and use the IFC and STEP technologies, a detailed explanation is not given.

Similarly, Kalay et al. (2001) propose that effective multi-disciplinary shared understanding can be enhanced through a combination of representational approaches and choose objects, project (assembly), and context as the domains of such comprehensive semantic representation. The three respective databases (the Object Data Base ODB, Project Data Base PDB and Context Data Base CDB) represent a "product model' which forms an ICDE integrated collaborative design environment) with the IDeAs (programming units, procedures, miniature expert systems, etc). They call this semantically-rich computational environment, P3 which consists of: (1) a shared representation of the evolving design project connected (through the World Wide Web) to (2) individual experts and their discipline-specific knowledge repositories; and (3) a computational project manager makes the individual valuations visible to all the participants and helps them deliberate and negotiate their respective positions for the purpose of improving the overall performance of the project. The authors describe integrated design environment that will facilitate collaborative decision making among the various participants. However, there is little description of how multi-disciplinary modelling occurs.

Lee et al. (2003) describe the DIMS (Design Information Management System) system. DIMS focuses on the representation of design information based on IFCs. It deals with schedule, estimation and structural engineering information. DIMS has the following capabilities:

- it can represent project information in multiple viewpoints. The viewpoints are; building spaces, activities, work classification and element types
- it can calculate quantities of each building component
- it helps users recognize corresponding 3D graphic objects in the CAD system.

While the core of the DIMS system is based on IFC 1.5.1, additional classes have been developed to model structural engineering information lacking in IFC 1.5.1. An Object-Oriented Database was developed to incorporate the IFC schema and other classes and support the persistency of the data. This OODB is integrated with a relational database since it is recognized that most current design information is held in relational databases. Rather than use VRML technology, visualization is carried out using Autodesk Architectural Desktop. It is assumed that the use of DIMS commences when the conceptual design is finished. While an object can be classified into several viewpoints, it is not clear how the different viewpoints are represented differently. The work described is very close to the aims of the Multi-view research stream of this CRC Project.

In knowledge representation, Bidarra et al. (2002) propose a multiple-view feature modelling which supports synchronous collaborative sessions via the Internet, guaranteeing the consistency between the part design and the assembly design views. Oldengram et al. (1998) present a multi-view visualization architecture (OBVIouS), using the concepts of the Open Distributed Processing – Reference Model (ODP-RM) as entities for visualization. It can visualize COBRA systems while they are operating. This research emphasizes the visualization of modelling, not the multi-database itself.

7.5 Key Issues for Multi-View Modelling Research

There has long been a notion that a single central model (e.g. building model) can be a source of information from which all required information may be drawn and used as the need arises. This notion recognizes that the graphic representation of an object is just that, one of many representations and not the only representation even though its graphic representation, i.e. the redescription of its form is an important one. Since the 1980s there was considerable work on producing such a central model, usually in the form of a database.

Since the early 1990s, there was a recognition that there is no single representation of an object and that different participants view things differently. Work by Nederveen and Tolman, Rosenman and Gero, McKellar and Peckam, Howard et al, and Amor and Hosking put forward an awareness of and different approaches to the concept of multiple views . Some work, e.g. the work of Clayton et al at CIFE purported to have a multi-view approach but worked on the premise that a model was created and different 'players' then staked claim to different parts of the model. It was never made clear who created the model in the first place and how such a model would suit all the needs of the different 'players'.

However, there seem to be different notions as to what views means. Some work, such as those associated with Gallicon, presents views as the graphic view, the schedule view, etc. Others think that multiple views means different graphical representations, e.g. line drawings as against a 3D view. This is not what a deeper notion of views means although it accommodates those notions.

A structural engineer and an architect view a building in different ways. To the architect a building is a set of spaces accommodating certain activities, where the spaces are defined by elements. This set of spaces and associated elements constitute a 3-D form (sculpture to architects). To a structural engineer, a building is an object that produces and transmits loads through its elements to the ground. The concerns of an architect are with form, space (spatial organization and communication) and the environment of such spaces as regards the performing of the activities and the senses, whereas the concerns of a structural engineers are with the stability, strength and integrity of the building system. Other disciplines have other concerns. All these concerns are founded on the particular functional interests of the discipline. Similar to the notion that a person who wears rose-coloured glasses see everything pink, each discipline sees an object in terms of its functional concerns. Such views 'colour' what is 'seen' by the discipline and hence what is modelled or represented. So that certain objects or properties are of interest to some disciplines but not to others. A door is of no interest to the structural engineer although the opening in the wall is. While a wall may be of interest to both the structural engineer and the architect, different properties are of concern. The structural engineer is not interested in the finish of the wall, whereas the architect is not interested in details such as the internal reinforcement.

Each discipline needs their own model to carry out their own work, the architect to examine aesthetic and certain environmental effects, the HVAC engineer to carry out thermal analyses, the structural engineer to carry out structural analyses, etc. So the models (or representations which include the graphic as well as property representations) are different for each discipline. Obviously all views and models must be consistent as they are after all representing the same object albeit in different ways. Also, obviously, one can think of a 'super' model as a union of all the models.

The work of Amor and Hosking and Howard et al. took a standard database approach of views (Amor and Hosking, 1993, Howard, H.C. et al., 1992). In this approach a database is composed of a number of 'primitive elements' and a view is some combination of such primitive elements. This, however, assumes that a 'primitive element' is represented by a single representation, whereas such an element, e.g. a particular wall is represented differently by different disciplines. If one thinks of the 'primitive elements' at a lower level, e.g. as the properties, then different property compositions can constitute different views of the same object and there is a correspondence between the approaches. Notwithstanding, the multiple view approach states that there is no single model to which everyone subscribes.

Previous work regarding information flows assumed such a single model view, which would be displayed in a Virtual world such as ActiveWorlds, where agents would help manage the operations on the model. This Project makes the point that there is no such model and, while there is collaboration between different disciplines, one has to take into account that there are several models.

Problems such as versions, who has the right to do what and when are problems common to all situations where more than one person works on a project and the project extends over time. These are generic problems and will have to be addressed in any working commercial application. However, the issues specific to the multiple view work are:

- what is represented in each model; what can be common to a number of models and what is specific to a discipline model
- how is consistency maintained among the models – the work of Pierra gives a possible answer

- how to represent the models – at present IFCs don't have a mechanism
- how to view the models
- how to link the different models to agent systems that operate in the Virtual World

When collaborating, different views will need to be accessible at different times to all the collaborators. The architects may want to explain some ideas on their model, the structural engineers on their model and so on. However, there are issues of ownership when the structural engineer wants to manipulate the architect's model and vice versa. The modes of working, synchronous or asynchronous may have a bearing as in a synchronous session there is control of what is happening.

8. CONCLUSIONS AND FURTHER WORK

This literature review has provided foundation work towards the establishment of industry requirements based upon a systematic evaluation of the potential of existing collaborative design tools. The specific ways in which advanced technologies for collaborative design may be studied in use in the industrial context will be derived from this work. In a parallel stream of research, the challenge of developing representations of multiple viewpoints for sharing, interrogating and manipulating design models is being undertaken.

Further work to identify design tools for use in this project is taking place. Commercially available tools have also been surveyed and a number of candidates for inclusion in the project empirical studies are being evaluated.

In order to make the Review results more accessible and with a view to informing the wider industrial community, a web site is under development. A set of research reports where further information is provided may also be found on this site. The site will evolve and be updated during the course of the project as new information is identified. The main tools that have been reviewed may be found on the project web site. For slide presentations see the Literature Review: http:www.arch.usyd.edu.au/~lcandy/crc

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The full set of supporting research reports may be found on the Project Literature review web site: http://www.arch.usyd.edu.au/~lcandy/CRC/home.html.

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