Chapter 1

Introduction - the road ahead

1.1 Setting the scene

Overview

The thesis is based on the argument that we know little about the process of design as it occurs within a real world context, and as a consequence have little understanding about how to provide technology to support it. We therefore need better ways to conceptualise design activity within its context of action. To bridge this gap in our understanding, the research in this thesis attempts to examine the mechanisms used to co-ordinate the work of engineering designers in the construction industry. This information is used to develop novel technologies that are appropriate to the needs and concerns of design workers in the domain, and is expanded to cover the larger area of design in general. A study of engineering design work *in situ* was performed and this was analysed within a framework based on the information processing metaphor of cognitive science. The results of the work demonstrate that design behaviour does not involve a simple mapping of problem onto solution as claimed by current research in cognitive science. Instead, behaviour results from the complex and interdependent interactions - of the organisational relationships between design workers, between individuals and artefacts, and between the individuals and their context of action. These interactions are crucial in determining the final outcome of the design process.

The understandings about engineering design generated through the study do not supplant current the understanding of design, but augments it by specifying the design process at a systems level, rather than at an individual level. This approach to the study of design is important in developing technology to support design work because it removes the emphasis on tools for problem solving by individuals and reassigns it towards tools to support human communication. For the technology to augment the design process, tools developed for communication must be integrated with the procedures involved in the organisation of work, the social protocols that the design workers use to manage informal communications, and the other artefacts that they use. This is achieved by detailing and making explicit the resources and constraints available to design workers in the construction industry. The results of the study allow technology developers an insight into the collaborative design process, demonstrating where (and on occasions, where not) technologies could be introduced to design work.

Background to the research

Historically, the thesis was intended to examine the role of models in the creation of a shared understanding of an ill-structured problem domain in design (for an overview, see Perry and Thomas, 1995). However, initial pilot studies demonstrated that the area was difficult to penetrate because design work was temporally, geographically and organisationally distributed. These studies also demonstrated that the study of models could not capture the complexity and richness involved in developing solutions to design problems because they only capture the results of problem specification, decision making, and negotiation. Whilst models could provide a mechanism for communication, studies into their use could not capture the full role of context that was apparently integral to the design process. Context, including the organisation of participants, the cultural background to their understandings, the setting, and all of the other factors that contribute to the generation of what sociologists call intersubjectivity needs to be taken into account when considering the activities that make up design.

The central role of context in social interaction and tool use in design led the direction of the research into an examination of design within a setting that took into account the interplay between the various features in the situation. The construction industry was selected as the research domain because it offered an area where this could be observed. The work of design in construction was also of interest because it allowed the examination of an area that had not been considered in detail before in the study of computer supported collaborative work (CSCW), opening up a new domain that could be used to inform other areas of research into collaborative work.

Motivation

The work conducted in this thesis is motivated by both theoretical and practical concerns. The theoretical motivation of the study is to generate a better understanding of how engineering design operates in a real world setting, involving multiple agents, constrained by its contexts, and drawing from resources in the environment. It involves an examination of the situated nature of the design process, distributed over its participants, tools and settings. The thesis draws from, and develops, a framework of distributed cognition to examine the microstructure of engineering design in a real world setting, one that is rich in physical and cultural resources for organising behaviour.

Alongside this theoretical motivation is a very practical and industry centred concern. This is to use a deep understanding of collaborative design to develop computer based tools and communications technology to support real world problems and contexts of use. In the thesis, the setting chosen involves the construction industry, where advances in materials have allowed designers to build more and more complex structures. However, commercial pressures have demanded that work be completed faster and more cheaply than before. These changes have led to problems as the designers have had to juggle with increased demands on their time and skills. In order to solve this problem, the industry has attempted to foster improved collaboration between design workers. Information technology has been proposed as a possible solution to this, through the introduction of 'groupware'.

Groupware technologies have the potential to support group work, by allowing co-workers to communicate with one another with a wider range of media than more traditional communication methods. However, simply increasing the range of communication media and the bandwidth available may not provide appropriate support for co-ordinating collaboration: more communication will not necessarily lead to better communication. Information technology needs to be implemented in a form that is appropriate to the situation of its use. This can only be determined by carefully examining the work and problems faced by designers so that the technologies introduced are suitable and meet the needs of the users in the performance of their work. The thesis attempts to provide this information.

Work from the thesis has already been incorporated into the CICC project[1] where it has contributed to several aspects of preliminary systems development. The thesis is therefore located centrally in the domains of computer supported collaborative work and user centred system design, where the concerns of the users of technology are brought to the forefront. Consequently, the demands of the task are analysed from a human, rather than a technological, perspective.

Distributed cognition

Distributed cognition is a theoretical approach that can be used to examine collaborative work systems, and offers a means of penetrating the area of context. The most developed framework of distributed cognition describes the organisation of cognitive work in complex settings, and most notably in the navigation of large ships (Hutchins, 1995a). Using distributed cognition as a framework, comparisons can be drawn between design and navigation, offering a metaphor where the design engineers 'navigate' through a design space, using a number of tools. Collaborative behaviour is mediated through socially encoded channels of interaction in a predefined, but adaptable, organisational structure. An analysis of navigational

[1] Collaborative Integrated Communications for Construction - ACTS Project 017

practice that includes culture, organisation and multiple artefact use clearly has parallels to engineering design. This thesis draws upon these parallels to explain how design work is co-ordinated in the setting of a construction engineering project.

The distributed cognition framework proposed by Hutchins was developed particularly with system design in mind for CSCW (Halverson and Rogers, 1995), using techniques that focus on the mapping of information flows that relate to design requirements (Shapiro, 1995). DC research focuses on the analysis of complex, socially distributed work activity in which technological and other artefacts form a central role; it is therefore an ideal method to use to discover the social and cultural dimensions of collaborative design, relating these back to systems development.

Central to this thesis is the idea of design being distributed over a number of people using both sophisticated and non-technological tools. By organising themselves in a particular way, designers can utilise the emergent properties of the system to generate design solutions to the engineering problems that they face as a group. Thus, the processes of cognition between the collaborating designers are examined through an empirical study, and principles about the way that design is organised and conducted are formulated.

Much of what we understand about the processes of cognition has been learned from cognitive and experimental psychology in laboratory settings. There are advantages in using a carefully controlled, experimental approach to analyse the mechanisms of human problem solving in exposing the architecture of their cognitive structures through the representations used and the processes involved in reasoning. However, when we attempt to apply this experimental approach to real world domains, such as engineering design, we find that it has several problems. These problems occur largely because of the huge number of relevant variables acting on the situation. In general, experiments can only tell us about how individuals perform tasks within very small and artificial domains, and when they are unaided by tools and information that exists in the environment. The failures of experimental cognitive science to deal with real world situations have led to ‘the turn to the social’ (Anderson, Heath, Luff and Moran, 1993), and this has been most noticeable in the area of CSCW where sociological and anthropological methods have achieved particular prominence (Anderson, 1994).

Whilst it has many advantages over the conventional experimental approaches, the turn to the social has not been unproblematic. The methods and techniques used by social science have been hard to adapt to the design of technology. This is largely because of their historical detachment from a practical application of the understandings that they can bring to problems. Nevertheless, the social dimension and the possibilities that such analysis brings to systems design has transformed the perspectives of technologists (Anderson *et al*, 1993), sensitising them to the social aspects of technology use. In particular, the ethnographic method - an anthropological approach to collecting information on the problem domain - has become a central feature of CSCW, achieving a degree of acceptance in the wider domain of human-computer interaction and information systems development (Anderson, 1994).

This thesis draws from a number of disciplines; it is truly interdisciplinary in that it employs different analytic approaches and empirical methods to any of the individual component disciplines, crossing the boundaries between them. Analysis of systems using DC permits the inclusion of all of the significant features in the environment that contribute towards the accomplishment of tasks. This is something that the individual disciplines - psychology, sociology and anthropology - fail to do because of their academic concerns and motivations. None of these component disciplines are applied sciences, and as a consequence they are not problem centred, calling into question their immediate value to systems design.

Simon (1981) has suggested building a ‘science of the artificial’ in which the structure of the physical environment is studied to examine how it interacts with the task in hand. This science would explore the range of internal processes that humans use to organise their activities within their environments. DC goes a step further than this, in suggesting that it is not just the physical, but the organisational and social setting that contributes to this structuring of activities (Halverson, 1995). A DC perspective is therefore particularly appropriate to examine the concerns and problems faced in collaborative design because it considers the social, organisational and technological components of activity (Rogers and Ellis, 1994). All of these may contribute to behaviour in real world settings, and all are therefore of direct relevance to the developers of collaborative technology.

Representations and cognitive science

Analysts require a means of describing the components within a system to explain the mechanisms that co-ordinate groups of collaborating designers, or indeed, any co-operating group. In cognitive science, these properties are described in terms of the representations and processes of individual thought. This cognitive framework can be expanded to examine larger units, to include individuals interacting with external representations, and the interactions of multiple individuals in a work setting. The cognitive process, as proposed by Hutchins (1995a), involves computations ‘through the propagation of representational state across a variety of media’ (p.xvi).

The cognitive sciences have historically focused on the information processing capabilities of a single individual, which involves an examination of how perceptual information is represented and processed to result in behaviour and actions. In socially distributed cognition, a larger granularity of analysis is selected - that of the group: it may consist of any number of representations, people, computerised artefacts or non-technological artefacts. Many processes can mediate activity between these representational states, so that incoming information be processed into an output by the larger cognitive system. This can be seen more clearly in the diagrams below (figs. 1a & 1b), adapted from Halverson (1995). These diagrams illustrate how a framework to examine the internal process of cognition (fig. 1a) can be expanded to a larger unit, the group (fig. 1b), using the same categories - input, output, process and representation.

Fig 1a. Mental Cognition

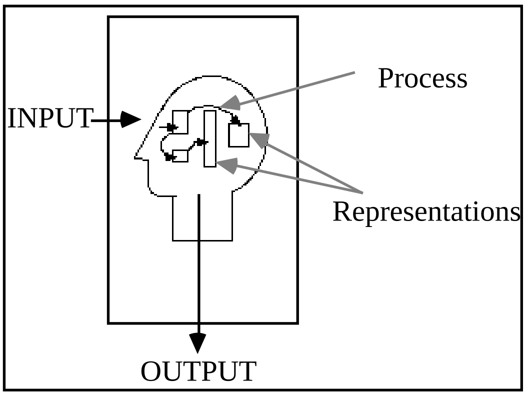
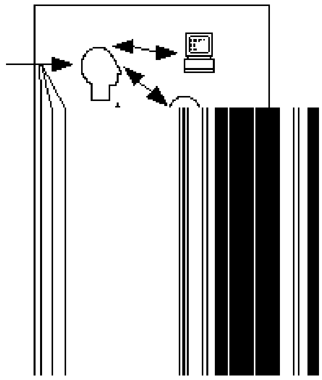


Fig 1b. Distributed Cognition



People work as individuals. The fact of this is inescapable: people do not think as a group, but as independent agents. However, through co-operation, individuals bring unique skills and resources to problems that they can use in conjunction with one another to solve their shared problems. The co-ordination of these resources is crucial to the co-operative activity that they are undertaking. This is analogous to the human cognitive system: in deciding what to do in a given situation, for example in catching a ball, the perceptual system must locate the visual position of the ball, the cognitive system must both understand that the ball must be caught, and communicate this to the motor system which must move the body into a position that enables the ball to be caught. This takes place with feedback occurring at every stage. Failure of the co-ordination mechanisms will usually result in failure to catch the ball. The same case exists in multiparticipant design activity. Each agent brings resources to the problem and must engage in communicating their ideas to the other participants, using feedback to modify their behaviour in the light of the other agents' activities. Failure to co-ordinate these mechanisms will result in the failure to produce a good design, or a design at all.

Technology and the division of labour

One of the problems in performing collaborative work, and engineering design falls into this category, is organising the task into component parts that can be performed by individuals. This must be managed so that the parts can be integrated back together again after the component parts of the task have been processed. Attendant to this process is an issue of co-ordination to ensure that the individually assigned parts are performed both correctly and in a form that can be re-integrated with the whole. Hutchins (1995a) describes this as the 'division of labour' and demonstrates how it is mediated through social, cultural and organisationally determined protocols in a navigational context. Difficulties in the process of distributing work can arise through individuals not performing their set roles, but also because the individuals fail to co-ordinate their behaviour to perform the task. Improving the process of distributing this labour through better co-ordination of work can be achieved by reorganising the way that the work is broken down. This can be effected either through organisational change or the adoption of new technology. However, the social organisation of work and the use of technology are highly inter-linked, each interacting with the operation of the other, so that neither can be considered in isolation (Grudin, 1993).

Individuals can be aided by developments in technology that enhance their productivity through aiding their creativity, memory, information processing capabilities and other human 'inadequacies'. However, it is how an individual's performance can be integrated with that of others that is crucial to the performance of a group. The use of communication facilities by themselves will not of themselves necessarily result in better co-ordinated work; however, when used appropriately, they can allow individuals to work together more effectively. This demonstrates the two crucial elements in collaborative design: the work itself (the design task), and in co-ordinating the division of labour (articulation work). Both of these are forms of work - so not only must a design be created, but the task of design must itself be organised and managed. In practice however, the two evolve together, as the understanding of the design problem and its solution develop over time.

In a thesis ostensibly in the domain of computer science, it may appear strange that technology is not the central theme, but it is not the study of technology *per se* that can inform us about collaboration and how to support it most appropriately. Central to collaboration, or people working together to perform a common task, is their organisation. Computers can be an integral part of this, but they do not form the whole picture. Many influences can affect the design process, and how to organise the resources available most effectively for the task in hand is an important issue to consider in systems design. The two disciplines that have considered this are human-computer interaction (HCI) and computer supported co-operative work (CSCW).

HCI, CSCW and the design of technology

There are many possible interpretations of what is meant by HCI. The term “HCI” is used in this thesis to focus particularly on user centred design and cognitive engineering. Its remit is to develop technology that makes use of our knowledge about the capabilities and skills that humans have, and to take the ‘cognitive load’ off the user by supporting them with augmentative computerised tools. This perspective therefore seeks to adapt technology to the human users at a cognitive level. The practitioners of these disciplines insist that the designers of technology must have a competent and well informed understanding of the abilities and limitations of the human users, so that the technology introduced is appropriate and usable for the task in hand.

CSCW moves the study of HCI from a focus on the individual towards that of multiple, co-dependant users, incorporating a perspective on the social organisation of work (Hughes, Randall and Shapiro, 1992). CSCW research therefore involves the analysis and development of tools and technologies to support the interactions of co-workers. Previous work in interpersonal computer communications, such as computer mediated communication (CMC), has focused on the widening of communication bandwidth between collaborators, with technologies such as email (Sproull and Kiesler, 1991) and video-conferencing (Kraut *et al*, 1994). However, with more recent work, and particularly since the inauguration of the CSCW and ECSCW conferences, a new understanding has developed. This suggests that we need to support the *work* itself that people are performing, and not just increase the volume of communication between collaborators, which may simply overload them with information. This necessitates a close examination of work and the context that such work is performed within. The role of context has become a central feature of work within CSCW, although researchers are only beginning to investigate how this can be used in systems design, and developing methods to collect the relevant material for workplace analysis.

To support activity systems with technology, it is also important to understand their information processing requirements so that technology can be implemented without disrupting activity by removing the resources used in co-ordination (Brown and Duguid, 1994; Halverson, 1994). When developing new systems that involve the transformation of work practices, maintaining the resources used in co-ordination may be as critical as that of proposing augmentative technologies.

The central aim of CSCW is 'to *understand*, so as to *better support*, cooperative work' (Bannon and Schmidt, 1991, p.51). Its central concern is to aid "work" (Grudin, 1993), through the use of appropriate technology, where 'groups' of people who share the same goal, perform work to achieve that goal through the co-ordination of their individual tasks. One area that has been spawned by CSCW is computer supported co-operative design (CSCD), using technology to facilitate the design process (Bødker *et al*, 1988), and this is the area that the thesis will develop. It achieves this by providing a deeper understanding of the work involved in collaborative design so that the technology developed is appropriate to the task it is intended to support.

1.2 Research Aim and Objectives

The thesis

The thesis put forward is that design is a cognitive activity that may be distributed over its collaborating participants. The co-ordination of their activities is mediated socially, organisationally and through the use of artefacts, involving the propagation of representations (Hutchins, 1995a) amongst the collaborating design workers.

...Aim

The primary aim of the thesis is to provide a deeper understanding of the domain of enquiry - design - through the application of cognitive science - distributed cognition - to support an applied activity - systems development. The applied aim of the thesis is therefore to extend our understanding of design to support collaboration between designers through the development of appropriate technologies.

...and Objectives

The thesis will involve a detailed examination of design workers, making explicit the mechanisms through which their work is performed. In addition to demonstrating the microarchitecture of collaboration between designers, this knowledge must be in a form that can be applied to the development of technological artefacts to aid designers.

The study is intended to inform system designers in the development of new tools, by examining the role of organisation in the engineering design process and to examine how the technological artefacts and the organisation of work are co-dependent. The understandings achieved from this work can also be used when reorganising the engineering design process, to determine which features of the system to leave unchanged (Halverson, 1994).

The objectives of the thesis are shown in the table below (table 1.1):

Table 1.1. Thesis objectives.

Theory and Method Selection	**Description of Work Activities**	**Analysis of Data Collected**	**Design Implications**
Select and develop analytic framework and method of data collection.	Gathering and representing data on the problem domain.	Application of analytic theory to data. Identify underlying organisation of work.	Suggestions for technology to support design activities.

In conclusion, the thesis involves the development and application of a framework for examining collaborative engineering design. This framework is used in combination with an appropriate method of data collection to develop a novel understanding of what ‘collaborative design’ involves. This will demonstrate the role of organisation in design, how engineers and design workers create, modify and communicate representational artefacts, and how these processes direct and co-ordinate the design process. The results of this analysis will present and structure this knowledge in a form that can be used in the development of computer technology that is appropriate to the needs and requirements of the design workers within a real world setting.

1.3 Scope of the thesis

The scope of the work described in the thesis covers engineering design in the construction industry. It is intended to provide a description of the problem solving and information processing work performed by design workers in the terms provided by cognitive science. The terms used by cognitive science are those of the representations and processes used in transformational work (or information processing), and these are instanciated in the people, artefacts and context involved in design. It is acknowledged that the representations and processes may not provide a complete understanding of the activities performed by the design systems examined, but they are the central focus of *this* enquiry. In addition, the study may provide insights to the understanding of collaborative work outside design in construction, although this is not its direct intention.

1.4 Related work

The body of work documented in the thesis draws from a rich history of existing work in psychology, sociology and anthropology, alongside more recent endeavours in CSCW. The theoretical basis of the analytic technique is derived from cognitive theory, and the methods used in the data collection have a basis in the research techniques used to examine different cultural and social patterns. Work in CSCW has focused on the objects used in social co-ordination. It has also attempted to make the theoretical concerns of its academic, parent disciplines relevant to the applied domain of systems development. However, the co-ordination mechanisms used in collaboration have not been examined in detail within the construction industry, and the framework of distributed cognition has not so far been applied to the design process.

The work most similar to that discussed in this thesis lies in the examination of cognition in groups (Hutchins, 1988; 1995a; Rogers, 1993) and in the study of the 'objects of co-ordination' in CSCW (Heath and Luff, 1991; Robinson, 1993a). The studies of distributed cognition show how work is enacted through interactions between people, artefacts and their environments. Studies into the objects of co-ordination demonstrate how people collaboratively interact with each other through the artefacts of work. Whilst these two areas are by no means the only sources of inspiration from which the work in the thesis draws, they are important influences on the development of the approach taken in the thesis.

Although a large body of research exists on collaborative work, behaviour is highly situated and context dependent, and thus previous research cannot be used to draw direct parallels to that documented in this thesis. This problem with relating previous work to individual settings has been used to argue that existing research in collaborative behaviour cannot answer questions across different settings. Whilst this is partially true, such a strong stance is not taken in the thesis, and other studies are drawn from in an attempt to understand the behaviour observed. It is also hoped that the implications of this research will reach outside the domain of engineering design in construction to other areas of research. Whilst collaborative design has some unique features, collaboration involves social activity that draws from a common culture and a number of semi-ubiquitous artefacts. The research findings may therefore be broadly applicable to other areas of human activity.

1.5 Structure of the thesis

Chapter 2 - “Communication, Co-ordination, and Collaboration in Design” - This chapter sets the context of the thesis and discusses the problem domain of both collaboration and design. This chapter also includes a literature survey of competing frameworks for the analysis of the problem domain.

Chapter 3 - “Distributed Cognition in Collaborative Systems” - Introduces the framework for the analysis of the data - distributed cognition. It argues for the need for this approach and provides a theoretical basis upon which to build the analysis. It describes the method used (an ethnographically based technique) to collect the material that will form the empirical foundation of the thesis.

Chapter 4 - “Applying distributed cognition to design” - This chapter considers the organisation of design in terms of a distributed cognitive architecture, and discusses how engineering design might be distributed over its participants, tools and environment, grounding this in the context of the construction industry. It then examines the role that the research will take in informing the development of technological systems to support design workers. Finally, the chapter introduces the field study designs and explicitly links the proposed data collection to its analysis.

Chapter 5 - “Data Collection - Collaboration in Construction” - The chapter examines data from the field studies in depth. It illustrates how the data was collected and how distributed cognition was used to frame the field studies by taking one of the field studies and examining it in detail. Distributed cognition was used to identify information processing in the design system through its inputs and outputs, processes and representations. In practice, this was performed on the field studies through examining the task, the goals, the participants, the artefacts, the resources and constraints, the transformational activities and co-ordination mechanisms used by the design system.

Chapter 6 - “Synthesis - Distributed Cognition, Design and the Development of Technology”. The chapter examines the data collected in the fieldwork to demonstrate the mechanisms used to co-ordinate the performance of design work. In particular, the chapter considers the role of shared artefacts in design, the organisation of the design process and the co-ordination processes that allow the problem solving aspects of design to be distributed across a ‘functional system’. It shows how the patterns of organisation and communication observed generate the cognitive properties of the design group and demonstrates how representations are used both as a means of *organising* and *undertaking* collaborative design. This involves formulating a generic understanding of engineering design, considers the cognitive properties of the functional system, and the implications of this understanding for the design of technology.

Chapter 7 - “Conclusions and Issues for Further Research” - Brings together the research covered in the thesis, drawing together the background literature and the study itself to examine how these can be integrated into a unified whole. It summarises the findings of the study, examines the implications of the thesis for systems development, and explores how the perspective of distributed cognition can help to inform the development of such technologies. The chapter concludes with future directions for research arising from the study.

Appendix A - “Fieldwork - Design Activities in the Workplace” - The primary appendix of the thesis, from which most of the examples described in the thesis are described. It presents a detailed description of the data collected in the workplace studies, with particular reference to the people involved in the work activity, their relationships to one another, the procedures that they followed, the tools that they used in performing work, the situations that actions occurred within, and the social interactions between them. The material is structured according to the demands of distributed cognition, examining the inputs and outputs to the work system, the representations involved and the processes used to transform these representations.

Appendix B - Fieldwork collected in a second organisation is presented (a consulting engineering partnership known pseudonymously as BEG). This material supports the fieldwork presented in chapter 5, covering in detail one area in the cycle of design (the structural design phase). A common structure to that of Appendix A is used to present the field data. This material is referred to in the thesis, although it is not critical to the arguments put forward.