# DISTRIBUTED COGNITION AND COMPUTER SUPPORTED COLLABORATIVE DESIGN: THE ORGANISATION OF WORK IN CONSTRUCTION ENGINEERING

A Thesis submitted for the degree of Doctor of Philosophy

by

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## Abstract

The intellectual contribution of this thesis lies within the area of computer supported co-operative work (CSCW), and more specifically, computer supported co-operative design (CSCD). CSCW is concerned with the development of information systems and technological support for multi-participant work activities. Research into CSCW seeks to understand how people and organisations interact with one another, and to integrate this understanding with the development of computer based tools to support real world settings.

Much of the technology developed to support the work of designers has been developed to aid individuals working alone, with tools like computer aided drafting (CAD), scheduling, and database software. The growth of interest in 'groupware' has led many technology developers to adapt these design tools for use in group situations. However, joint activities are different from those performed alone, and organisational structures can both interfere with, and supplement co-operative work practices in a way that the current technologies cannot provide support for. To develop effective group design tools, we need to understand more about collaborative processes in design.

This thesis draws from the theoretical underpinning of cognitive science and the methods of anthropology and sociology, in an interdisciplinary study of design performance in the construction industry. Fieldwork is used as a method of qualitative data collection and this is examined within the analytic framework of distributed cognition. The results of this analysis provide a useful and usable description of the work of design that technology developers can use to support collaborative design work. In line with the methods of distributed cognition, the activities observed in the workplace studies are examined in terms of their *processes* and *representations*. The resources that were available to the design participants are made explicit, as are their situation-specific work patterns.

Two case studies of design are examined. The first of these describes design work in a civil engineering project, which involves a number of different design activities. The second describes the work of consulting engineers in building design, focusing on a more limited design role, which is used to back up and supplement areas of the first study that were understood to be particularly relevant.

The findings of the study demonstrate how design processes operate simultaneously at personal, organisational and inter-organisational levels. The distinction between the formal, organisational procedures, and the informal, social processes that compliment them is examined to show how these are interrelated in the performance of the design task and their importance to the mechanisms used to co-ordinate actions. The findings of the study have implications for the development of novel technologies to augment the engineering design process, and have already been used in the development of assistive design technologies.

The thesis demonstrates that the framework of distributed cognition can be used in the analysis of cognition within a setting, involving multiple individuals, in concert with 'natural' and 'artificial' artefacts. The thesis makes clear a number of processes in design that can only be examined from a perspective which includes the social dimensions of work. The methods of study focus on the resources in collaborative activities, whilst the analysis, structured in terms of the representations and processes of collaborative activity, shows that the method can be used effectively in the development of CSCW and CSCD technologies.

***Keywords:** Collaborative Design, CSCW, Distributed Cognition, Engineering, Construction.*

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# Acknowledgements

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This thesis is dedicated to my mother and my father.

# Publications and Other Material

The research described in this thesis was conducted between March 1994 and November 1997.

Some of the material contained in the thesis has already been presented in the following material. These include published papers, submitted papers, papers in progress and technical reports, and consultancy reports. The consultancy reports were a condition of entering the workplace and are non-academic, but offer further insight into the settings observed and the problems encountered by the participants in communication and the co-ordination of their work.

## Published Papers

PERRY, M.J. & THOMAS, P.J. (1995) Externalising the Internal: Collaborative Design Through Dynamic Problem Visualisation. *Adjunct proceedings of BCS HCI'95 Conference: People and Computers, August 29 - September 1st, Huddersfield, UK.* Eds. Allen, Wilkinson & Wright, p. 149-154.

PERRY, M. (1995a) Artefacts in collaborative design. Poster. In the conference supplement to the fourth *European Conference on Computer-Supported Cooperative Work, September 10-14, Stockholm, Sweden.* Eds. Sundblad, Tollmar, Reignier, Fahlén & Forsyth, p. 37-38.

PERRY, M.J. (1995b) Cognitive Artefacts and Collaborative Design. *IEE Colloquium: 'Design systems with users in mind: the role of cognitive artefacts'.* IEE Computing and control division (C5, Human-computer interaction), Digest no. 95/231. Also exists as a computer science technical report at Brunel University (CSTR-96-8).

ROSENBERG, D., PERRY, M.J., LEEVERS, D.R.A. & FARROW, N. (1997) People and Information Finder - Informational Perspectives. In the Social Shaping of Multimedia Workshop, Edinburgh. *COST A4 Series Report.*

## Unpublished Papers and Reports

PERRY, M.J. & CONDON, C. (1996) Off the drawing board: design in civil engineering. Short paper *(i.e. Centre discussion document).*

PERRY, M.J. (1996) Co-ordinating Representations: the Flow of Work in Civil Engineering *(i.e. Centre discussion document).*

PERRY, M. & SANDERSON, D. (1997) Co-ordinating Joint Design Work: The Role of Communication and Artefacts. *Submitted to Journal of Design Studies.*

PERRY, M.J. (1997a) A personal examination of the issues faced in conducting workplace studies. Presented at the *ECSCW'97 Workshop on "Workplace Studies: Theoretical and Practical Issues".*

PERRY, M. (1997b) Process, representation and taskworld: distributed cognition and the organisation of information. Submitted to *ISIC'98 - Information Seeking in Context: an International Conference on Information Needs, Seeking and Use in Different Contexts.*

PERRY, M.J. (1997c) A review of task analysis and task modelling for the CICC project. *CICC Project Document.*

PERRY, M.J., CONDON, C.C., ROSENBERG, D., LEEVERS, D.R.A. & FARROW, N. (1997) B14: "Before" Report (psycho-social issues). *CICC Project Document.*

ROSENBERG, D. & PERRY, M. (1997) Editorial on ECSCW Workshop submissions. Presented at the *ECSCW'97 Workshop on "Workplace Studies: Theoretical and Practical Issues".*

PERRY, M. & ROSENBERG, D. (1997) The application of distributed cognition in workplace studies. *In Progress.*

BROWN, B.A. & PERRY, M. (1997) Why don't telephones have off switches? Ringing phones and Normative Procedures. *In Progress.*

## Consultancy reports generated from the Fieldwork.

These reports were generated from the fieldwork conducted on the thesis, but are confidential (pseudonyms are italicised). They offer additional material that was not possible to include in the thesis, and are available to vetted personnel on request. All reports were authored solely by Mark Perry.

1. An initial report on communications infrastructure on the *ConsCo* road construction project.

2. Team Communication Processes on the *ConsCo* Road Construction Project

3. Inter-team Communication on the *ConsCo* Road Construction Project

4. The Flow of Communication Between the *Temporary Works Designer* and *ConsCo* Construction Sites

5. A Review of Communications at on the *Roman's House* Project.

6. An interim report on *ACEO* communications infrastructure and involvement in The *Roman's House* project.

7. Preliminary report on the implementation of *proprietary software* and CICC technologies at *a site.*

8. Experiences of remote users on *proprietary software* and CICC technology at *a site*. (Supplementary report to 7.).

# 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

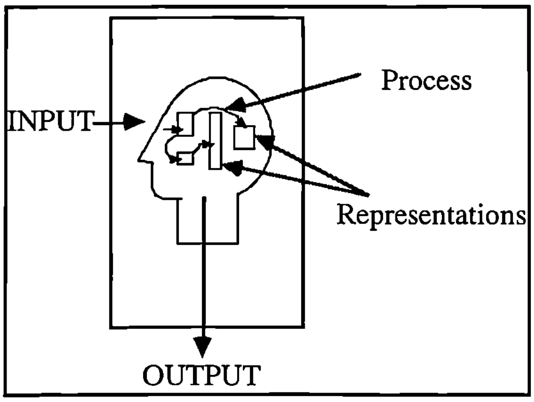
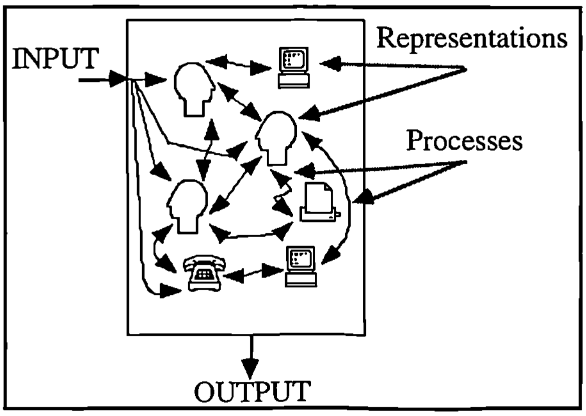



Fig 1b. Distributed Cognition




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 collaborativ 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.

# Chapter 2

# Communication, Co-ordination, and Collaboration in Design

## 2.1 Four elements and a theme

The objective of this thesis is to make explicit how collaborative design is co-ordinated so that it can be supported through the use of appropriate technology. The chapter develops the background to this, laying the foundations upon which research in the thesis will be developed. The four elements central to the thesis are therefore carefully examined in detail: co-operation, collaboration, communication, and co-ordination. This involves examining the issues surrounding collaboration, and the methods for examining collaborative work. The nature of design is also examined, showing where gaps in existing research exist, and where the research forming the basis of the thesis strives to make a contribution. Finally, techniques for developing technological systems to support collaborative work are explored in the application of social science to systems development.

The terms of co-operation, collaboration, communication, and co-ordination are ill-defined and used in a confusingly range of ways in the literature (see Oravec, 1996). In order to better understand the distinctions between them within the scope of this thesis, they are defined below:

**Co-operation** - A form of activity that involves individuals working together, using each other as resources for learning, sharing cognitive tasks, and as memory aids. To achieve co-operation in work, individuals must somehow co-ordinate their behaviours, by sharing their goals, plans and motivations with each other. When engaged in joint activities, actions must be negotiated to synchronise and co-ordinate individual activities, so as to avoid conflict (Norman, 1992). This exchange of information is managed through interaction and communication between the participants.

**Collaboration** - The work that is carried out by people who are acting together; it is a subset of co-operative work, differing in that the individuals share a single goal that is larger than their individual goals (Branki *et al*, 1993). Collaborative work is more than an individual effort: it involves the aggregation of many plans and goals held by individuals which are subsumed into a greater task. It involves agreeing on the shared goals, planning the allocation of responsibility and co-ordination, and keeping track of goal solving progress (Terveen, 1995).

**Communication** - Defined as the exchange of information (Connors, Harrison and Summit, 1994). Communication is the process by which individuals make known their wants, needs, expectations and future behaviours to others. This may be achieved through verbal and non-verbal forms. Communication is the cement that binds the organisation together; the greater the need for co-ordination and co-operation, the greater the necessity for communication (Brehmer, 1991). However, communication requires resources (both mental and physical) that are additional to the task being performed.

**Co-ordination** - The process that allows individuals to work together, which involves communication between the participants. Malone and Crowston (1993) define co-ordination as 'the act of managing interdependencies between activities to achieve a goal' (p.379). Through organising themselves into a unit, individuals can perform complex work distributed over time and space. Co-ordination is the means by which the distribution of labour is achieved, and may arise through the actions of an 'executive' (management role), or through emergent properties of the work that allow 'naturally arising' co-ordination.

Defining the relationship between these elements clarifies the nature of what is meant by collaborative design: communication is the mechanism used to co-ordinate co-operative and collaborative behaviour. Communication, by itself, does not cause collaboration, and simply increasing communication will not necessarily cause better collaboration. Co-ordination involves bringing together individuals so that they can work in a purposeful way, both breaking activities into parts that can be performed by individuals, and putting these parts back together to achieve a collective goal. This must involve communication at some stage. Collaboration appears to be mediated through socially encoded protocols (Ellis *et al*, 1991; Hutchins, 1995a), and it is these channels of communication that bring the actions of agents into co-ordination with one another to perform productive work. If technology developers are to generate a means of supporting collaborative design, it is essential that we understand the operation of these co-ordination activities to guide the appropriate use of these technologies (Marmolin, Sundblad and Pehrson, 1991).

If co-ordination is central to collaboration, computers and communications technology developed for use by collaborating designers should therefore focus on providing support for co-ordination events. As applied social scientists, we need to understand how this relationship between communication and co-ordination operates within the design environment, and how these are used to achieve a single, negotiated goal. Computers can support co-ordination not simply through just establishing a communications link between people, but by helping to co-ordinate collaborative activities and supporting joint problem solving (Bannon, 1986). This thesis therefore involves an interdisciplinary study of the nature of work, bringing together cognitive, social and organisational aspects into a unified understanding of how design is performed in, and across, organisations.

## 2.2 Collaborative design

### 2.2.1 The character of generic and engineering design

The meaning of the word 'design' has been hard to establish. Simon (1969/1981) defines design as being concerned with the state of how things ought to be, and with devising artefacts to attain goals; designers are those 'who devise courses of action aimed at changing existing situations into preferred ones' (p.111). The final goal of the design process, he continues, is to specify another artefact that solves the problem. The eventual artefact of the design process will set the initial conditions that the designers leave to their successors. The process of design, according to Simon is analogous to problem solving, where design involves a search process through a 'problem space'. However, this definition of design is not precise enough to use in an examination of engineering design. Attempts at reducing the scope of study were brought about by Simon himself (1973) who described problem solving activity as falling into a continuum between well-defined and ill-defined problem spaces, depending on their level of specification for goals and operators. Ill-structured problems are problems that have no clear definition: it is not always clear what the problem itself is, much less the solution, because there is not a fully specified goal, only an identified problem area. This more closely resembles the task of engineering design.

The term 'generic design' suggests that design is distinct from non-design activities, and that it can be abstracted from a specific task to a generalisation of a set of tasks that relate these activities (Schön, 1983; Goel and Pirolli, 1989; 1992). Design can be observed as moving through a sequence of steps: exploration and task decomposition, identification of requirements, solution of sub-problems in isolation, and combination of answers to sub-problems into a global solution (Alexander, 1964; Simon, 1974). Effectively, design involves determining that a problem exists (although it may be unclear at an early stage) and having a set of possible resources available to solve it, which may include, capital, time, intellect and physical materials (some of which may be interchangeable). Designers then match the available resources to the problem, so that the original problem ceases to exist (Rzevski, 1981, 1984). However, in most circumstances there may be multiple ways that this mapping can occur - choosing between them is a matter of compromise, because there is no single, 'right' answer, just good and bad ones for a particular purpose (Rittel and Weber, 1984).

One cognitive strategy that *individual* people use with complex design problems involves task decomposition into modules. Task decomposition is used to combat complexity in design problems (Simon, 1973; Chandrasekaran, 1981; Thomas and Carroll, 1984), breaking the task into manageable work units. However, this may be over simplistic, because such modules can be highly interdependent upon one another (Luckman, 1984; Goel and Pirolli, 1989). In such cases, individually optimal sub-units of design are not necessarily optimal when considered over the design as a whole (Luckman, 1984). It may not be possible to break a design task into problem modules and then to integrate the component solutions; the interdependency of modules means that activities have to be dynamically co-ordinated to create a unified design. When *multiple* designers are involved, co-ordination of design modules moves outside the individual's cognitive domain into a social one, involving communication to co-ordinate the division of work. Group design, as well as being made up of individual cognitive problems, also involves building a problem space collaboratively - discovering what the collective problems are, as well as solving them collectively.

For an engineer, design is described as making something that has not existed before (Petrosky, 1982), and engineers tend to take the words "engineering" and "design" to be synonymous (ibid.). Petrosky describes engineering as involving the articulation of an idea and rigorously testing it to ensure that the designed solution can perform its desired function without failing, according to the specifications (set out by the client) and known standards relating to the components and their interactions. Design involves constant revision, where alternatives are narrowed down to a single form which becomes *the* design. Designers are therefore placed in a position where they have a huge number of possible solutions and must select the most desirable one (Alexander, 1964). This involves two operations that must be performed: firstly, the designers must generate a number of alternatives and encode these symbolically. Then, all criteria must be expressed in the same symbolism to allow comparison and selection of the most appropriate solution (Alexander, ibid.).

This engineering process appears to be far more grounded in the real world than that of 'generic' design elaborated upon earlier; yet at a fundamental level, engineering design relies on the underlying cognitive, social and physical factors (Rzevski, 1984) that characterise ill-structured problem solving. These 'real world' conditions are largely ignored in 'high level' cognitive analyses of design. However, these conditions, embodied in the constraints and available resources (i.e. the context, or situation) that actual design problems exist within, are central to engineering design (Bucciarelli, 1988, 1994). This occurs because the structure of the setting itself imposes organisation onto the activity that occurs within it.

### 2.2.2 Collaborating for design and designing for collaboration

Many designs cannot be generated by a single individual and involve the co-ordinated effort of many individuals (Curtis, Krasner and Iscoe, 1988; Günther, Frankenberger and Auer, 1996; Popovic, 1996) and there are several possible reasons for this. In general, this occurs when the workload is too great to perform within a limited time, and the technical skills required assume too much knowledge to be held by a single individual. As a consequence, many people become involved in the design of large systems, such as roads, buildings, manufacturing processes or computer products, and their activities are co-dependant on the simultaneous decisions of the other people and design groups working on these systems.

Simon (1973) discusses 'organisational design' (design by a hierarchically structured group) as an ill-structured problem. This activity begins with tentative specifications and becomes well-structured through subdivision into components that are solved by groups of experts who have been delegated sub-tasks, a process that involves negotiation to co-ordinate their activities. The organisation of the agents in the hierarchy itself makes the problem transparent - which is the goal of problem solving (Simon, 1981). Organisational design appears to be similar to the ill-structured activity characterising generic design: the problem domain and architectural implementation is different, yet the problem area clearly retains characteristics of its generic parent.

Large, multiple participant design projects necessitate close co-operation between their co-designers to allow the seamless integration of their work. However, collaborative design is a highly complex activity: decision makers and designers may have different problem conceptualisations, solutions and personal agendas that they wish to pursue, and which may not be compatible. The collaborating designers also may have different levels of problem understanding, and experience in different domains; the design is therefore emergent, arising from the combination of expertise and perspectives of the collaborators (Muller, 1992). This specialisation of intellect, combined with the complexity of a problem means that few, if any, participants will understand the design as a whole. Designers already have tools that can reduce individual cognitive demands, but designers could also be helped by providing tools to support the collaborative aspects of their work. Providing tools to support the collaboration of the various 'stakeholders' in design is therefore an important goal which has already been the subject of research in the CSCW community (e.g. Boland *et al*, 1992; MacLean, Young and Moran, 1989; Muller, 1992; Lu and Mantei, 1993).

In general, outside CSCW, social and organisational co-ordination issues have been largely ignored by technology developers and researchers (Anderson, Button and Sharrock, 1993), who have tended to concentrate on aiding individual problem solving (Cross and Cross, 1996), rather than on design co-ordination. However, little research has been conducted into the process of co-ordinating distributed work, in areas such as control, management, negotiation, delegation of responsibility and exchange that are central to group cohesion (Rogers, 1992). This divorce of work and co-ordination is artificial: collaboration is emergent (Schmidt, 1991; Goguen, 1994) and situated in the activity. It cannot be examined independently of its human context - the tools and processes of design themselves have aspects that help co-ordinate collaborative activity.

The 'process' of design has also been largely ignored in the literature on design in the cognitive sciences, as well as by commercial tool developers (as noted by Taylor, 1993 and Marmolin *et al*, 1991). Design aids, such as CAD (computer aided drafting), simulation and scheduling software have been developed largely for single users, not as collaborative tools, and their communicative aspects have been ignored. However, the nature of *process* is central to all design activity; designs do not suddenly leap from the mind to the drawing board - they are discussed, transformed into external representations, discussed again, compared to alternatives, tested, and so on. This process is iterative (Bucciarelli, 1988; Pidd, 1989; Taylor, 1993; Lu and Mantei, 1993), and to focus effort onto supporting the individual at a single snapshot in time means that many problems in design will not be addressed by technology and technology-oriented research. The potential danger of implementing technology that fails to accommodate this feature of design is the development of a technology that does not 'fit' the needs and expectations of its user group.

There is a gradual recognition that design is an iterative and collaborative process. This is illustrated in the development of concurrent engineering as an area of applied research. Concurrent engineering applies computer technology to propagate a design model throughout the design process (Easterbrook *et al*, 1994; Prasad *et al*, 1993). Its aim is to integrate all parts of the design and engineering process so that the design decisions made are based on the most up to date information available. This recognition of informational importance in design is clear evidence that design is perceived as a collaborative process, and that present technology is inadequate because it is based in the 'lone designer' paradigm. However, concurrent engineering has taken a technology centred perspective of design, and human interactions within the concurrent design process have not been considered in detail so far (e.g. LeBlanc and Fadel, 1993; Pohl and Jacobs, 1994; Anumba *et al*, 1997). Most research in concurrent engineering has so far been at a highly technical, architectural and implementational level, and as a consequence, little theory as to the mechanics of *how* people interact in design has emerged. System designers have only recently begun to consider these areas (Bentley *et al*, 1992; Heath and Luff, 1991; Robinson, 1993b, Easterbrook *et al*, 1994), and as concurrent engineering matures, greater emphasis may be placed on psycho-social and organisational factors.

The problem of providing appropriate technological support for design has become complicated recently through the development of commercially available technological infrastructures for communication. Technology has moved on from just involving the use of telephones to incorporate the fax, email, the networked computer aided drafting (CAD) system, and more recently, video-conferencing technology. These technologies have been introduced into engineering design projects, often informally, and have allowed designers to work in a way that was not possible even a few years before, an example of this being that designers are able to be spatially distributed even for projects that require a high degree of interaction. Projects now regularly involve companies in different locations, even trans-continentally, and there is the further possibility that current organisational groupings could fragment as designers no longer need to work in the same locations. Technology, however, can cause as many problems as it solves through mis–co-ordinating activity (for example, groupware masking the occurrences of breakdowns in understanding [Easterbrooke, unpublished]). Technology to support designers must therefore make use of a better understanding of the role of technology and communication in collaborative design.

Summing up, design can be classified as encompassing all of the features that the 'design activity' brings up. Design, in the real world, is not simply a particular type of cognitive activity, but is situated within a social and organisational context. Harrison *et al* (1990) claim that focusing on design as communication and not as a creative process has 'profound effects on how we view it and hope to improve it'. This idea is central to the thesis, because design is a socially mediated activity (Bucciarelli, 1988; Branki *et al*, 1993; Harrison *et al*, 1990, Radcliffe, 1996), as well as a cognitive one (Simon, 1981; Goel and Pirolli, 1989, 1992; Dwarakanath and Blessing, 1996). Communication itself is mediated through the transfer of representations, and focusing on these representations, or artefacts, that the communications are embodied in, should therefore prove a worthwhile research pursuit.

Although collaborative design has been extensively researched (e.g. Marmolin *et al*, 1991; Anderson *et al.* 1993; Bucciarelli, 1988, 1994; Branki *et al.*, 1993; Peng, 1994; Brereton *et al*, 1996; Cross and Cross, 1996), the mechanisms underlying collaborative activity in the workplace are rarely discussed. Additionally, a number of assumptions have been made about the design process in this body of work. These include assumptions on *who* the designers are (generally concentrating on white collar workers), *what* the design work involves (generally brainstorming activities), *where* the design occurs (office based work), and the *timescale* (short term computer support for meetings, rather than project support over months or years). These assumptions are challenged through a naturalistic study of the design process in later chapters.

### 2.2.3 Collaborative design as a communication issue

Communication is essential to co-ordinate and organise the collaborating participants in an activity. This communication can be achieved in a number of ways; it may occur through face-to-face meetings or, more recently, through telecommunications and computer technology. Communication between designers may be one to one, one to several or one to all, and it may be synchronous, partly asynchronous, or totally asynchronous. The communications they use may take many forms, via speech, non verbal communication, texts, drawings, photographs, or a combination of these. In addition, they may be consciously generated, or arise naturally (as an emergent phenomenon) out of activity. One feature of this multitude of communications is that they are hard to track and keep aware of, both for the design participants and researchers studying them.

One of the features of design is that it occurs on a representation (either mental or external) and not on the object of design itself (Simon, 1981). Working on an external representation, such as a calculator, CAD/CAM software, a database, or a simple pencil and paper diagram, allows a greater degree of flexibility for the designer than working with the details mentally: resources can be brought to bear on the problem that are not dependant on the cognitive structures present in an individual's mind. Many of these representations are visible to all of the designers and the representations are encoded in symbols that can be interpreted by many or all of the designers. This shared awareness is believed to be crucial in collaborative activity (Harrison *et al*, 1990; Dourish and Bellotti, 1992). These representations, or 'objects of co-ordination'[1], allow work to be propagated around a work system without the constant negotiation of understanding that would otherwise be required.

[1] Barry Brown, personal communication.

### 2.2.4 Mechanisms of collaboration - the 'objects of co-ordination'

When examining problems from a task based perspective (such as *'design'*), people can be observed to use a number of resources in work, including artefacts (tools) and other human agents. To solve a problem, these components must be organised effectively, so as to contribute to the task goal. Several studies have attempted to describe the nature of these co-ordination behaviours (e.g. Heath and Luff, 1991; Marmolin *et al*, 1991; Murray, 1993; Heath *et al*, 1993), although descriptions of underlying structure of the co-ordination activity have been elusive. This is partly because many studies in CSCW are underpinned with an atheoretical, ethnomethodologically motivated approach (see section 2.4.3), but also because real world situations are so rich in information that it is difficult to see any underlying structure without a framework to use in analysis. Such frameworks are only now being developed, driven by the recent need for studies of technology in use. Some of these are described below.

Rogers (1994) describes several forms of representation used to co-ordinate behaviour, some of which were designated explicitly in the organisation of work, whilst others were used informally. The task she describes involved drafting files on a networked CAD system, with several designers in an open-plan office. To prevent 'file clashes' when two people tried to open the same file (not a feature supported by the technology), a system had been organised where file users wrote up the name of the file they were currently using on a whiteboard. However, use of the system was not rigidly enforced: sometimes users just called out that they were using a particular file, at other times they called out and wrote down the filename, and at other times, they did not inform the other users at all. Various problems were documented with the different mechanisms used to co-ordinate file use. However, through making information public, users were creating a 'shared awareness' that allowed them to co-ordinate their behaviours and avoid clashes, each of the mechanisms having different costs and benefits. Rogers describes these co-ordinating representations as 'mediating mechanisms': representations that allow individuals to co-ordinate their behaviour with each other. These can arise as a natural product of work practice, or as described by Rogers, as a deliberately designed mechanism of co-ordination. Mediating mechanisms are a class of 'common artefacts' (Robinson, 1993a) where operations on these artefacts by one person can be used to co-ordinate the activities of others.

Robinson (1993a) uses the example of a hotel key rack to explain this. Simplistically, hotel key racks allow keys to be stored. However, the structure of the key rack is such that a number of other non-storage functions are possible. Thus, the key rack allows the receptionist to see whether a person is in the hotel or not, and messages can be stored with the key and handed to the occupant when they collect or deposit their keys. Common artefacts allow people to interact with one another *through* the object itself, as collaborating participants' activities are mediated and rendered visible through them (Heath and Luff, 1991; Robinson, 1993a). The use of common artefacts also means that collaboration does not have to involve face-to-face activity, and can occur through peripheral monitoring other people's work (Heath and Luff, 1991), through direct, or indirect observation of the results of actions performed on the common artefacts (Bannon and Schmidt, 1991).

Star (1989) discusses a similar form of artefact, the 'boundary object', which acts as a device for communication between diverse groups or individuals in a process. In the example given by Star, animal skins are used as a boundary object between trappers and museum curators. Neither knows much of the work of the other, but each can interact with each other at the 'level' of the pelt - it is the boundary where their worlds meet and the two groups can speak a common language. Henderson (1995) develops the idea of a boundary object into that of a 'conscription device', where engineering drawings are used as 'network-organising devices'. These drawings enable group activities, they act as receptacles of knowledge, and they can be further developed through the interactions of the collaborating participants. The artefact provides a common experience of the design, and can be transmitted between experts in different domains.

The 'objects of co-ordination' include a whole class of artefacts that are used in work processes as a medium for both getting the work done, and co-ordinating that work. They enable collaboration to arise by allowing the natural sharing and dividing of work (Bødker, 1993). These objects have a representational function beyond simply reorganising the cognitive task, because they extend the work into a social domain, by structuring work activities. The representations can exist in a number of different artefacts, generated, modified and transmitted between people, such as drawings, letters, forms, post-it notes, speech, and so on.

Within particular situations, certain representational media may be more appropriate in co-ordinating activities because:

- they are unambiguous,
- they may be able to be quickly interpreted and processed, or
- easily passed on to the next user of that information.

The most likely naturally arising objects of co-ordination in design are 'cognitive artefacts'. Cognitive artefacts are tools that aid thought (Payne, 1992), and are defined as 'an artificial device designed to maintain, display, or operate upon information in order to serve a representational function' (Norman, 1991, p. 17). Essentially, cognitive artefacts are tools to aid individual thought. However, Nardi and Miller (1989) describe how cognitive artefacts provide a point of contact mediating co-operative work, using a spreadsheet as an example of such a mechanism (it is therefore a common artefact). They propose that the visual clarity of the spreadsheet exposes the structure and content of the individual user models (of the work) to encourage sharing knowledge amongst different people. The emphasis of such research on common, cognitive artefacts has been one of the most fruitful areas in CSCW research, and has usually been centred on how the design of these artefacts can be improved upon to enhance their collaborative qualities (Hutchins, 1988, 1995b; Nardi and Miller, 1989; Heath and Luff, 1991; Tatar *et al*, 1991; Nardi, 1992; Boland *et al*, 1992; Hughes *et al*, 1992; Robinson, 1993b).

Not all communication occurs through physical artefacts, but when work is systematic and process based, such as engineering design (also navigation and piloting aircraft [Hutchins, 1995a,b]), and the process has itself been designed, their use appears to be commonplace. In these situations, the artefacts (encoding representations) move through a system, where they are operated upon, the outputs of which become the input to another part of the process. It is important that these artefacts flow through the system smoothly and require as little cognitive processing as possible to be interpreted or used by the receiving participants (Hutchins, 1995a). This is an area that CSCW can and should be examining.

### 2.2.5 CSCW - collaboration and technology

Computer support for collaborative design (and CSCW), involves two central points of interest concerning this thesis: it is involved in the study of the practices that constitute work, and in developing technology to support those work practices. The two have been hard to reconcile, one drawing its inspiration, language and techniques from the social sciences, the other developing technology (both hardware and software) from a software engineering and systems development perspective (Bannon and Harper, 1991; Robinson, 1993b).

Many research areas, such as information systems, groupware, computer-mediated communication and participatory design, have the similar concerns to CSCW, but the focus of CSCW lies in uncovering the requirements of co-operative work (Bannon and Schmidt, 1990) to use in the implementation of technology to support it. One of the distinguishing features of CSCW is that it draws from both multi-disciplinary[2]

[2] - being the use of many disciplines in combination with one another; for example carrying out psychological and social analyses in parallel.

and interdisciplinary[3] approaches, considering the psychological, social, organisational and artefactual dimensions of work.

This study draws from a background of workplace studies in CSCW, including studies of air-traffic controllers (Hughes *et al,* 1994), London Underground controllers (Heath and Luff, 1991), designers (Murray, 1993), a CAD group (Rogers, 1993), a printing organisation (Bowers *et al,* 1995), a clothing design company (Bowers and Pycock, 1996), and too many others to document in detail. Interestingly, many of these studies have not been centred on CSCW technology; they have been much more concerned with the activities involved in co-ordinating work. Some very general findings have arisen out of these studies, of which, possibly the most fundamental observation (Heath and Luff, 1991) was that of perceptual monitoring, where co-located workers maintained an awareness of each other (allowing the co-ordination of their activities) by observing the physical actions of the people working around them.

A number of technologies fall into the category belonging to CSCW, although several were in use even before the domain came into being. These include email, group editors - ShrEdit and GROVE (Dourish and Bellotti, 1992; Olson *et al,* 1992; Olson *et al,* 1990), tools for conflict negotiation and immersion scenarios, such as meeting support and GDSS tools (Karat and Bennet, 1990), including Colab (with Cognoter and Argnoter - Stefik *et al,* 1987; Tatar *et al,* 1991) and gIBIS (Conklin and Begeman, 1988), 'conversation' management (GroupLens [Resnick *et al,* 1994] and THE CO-ORDINATOR™ [developed from Winograd and Flores, 1987]), shared calendars, shared information spaces (Trevor, Koch and Woetzel, 1997), and video-conferencing and Media Spaces (Dourish and Bly, 1992). There are a huge range of technologies that have been developed to support co-operation and collaboration. However, the tools that have been developed tend to support only small groups of people and the tasks that they support have been restricted to highly focused domains of study. These tools are therefore not necessarily appropriate for supporting design work in construction. To understand how to develop and apply tools to a particular problem domain, such as construction or manufacturing, CSCW research must examine the nature of design as it occurs in the workplace.

[3] - being the combination of disciplines to form new methods and frameworks for enquiry; this might involve an interwoven psychological and social approach.

## 2.3 Cognition in design

### 2.3.1 Design in the wild

Design is traditionally thought of as a conceptual discipline, concerned with creating solutions for ill-structured problems (section 2.2). However, it is essential to recognise that design work is centred on activities based in the world and distributed over a diverse range of people and organisations. It is not only a mental, but a situated activity in which a number of constraints act on the design process. Simple, low level task analyses and laboratory studies cannot capture the form of information required to inform system developers about these real world activities. To develop assistive technologies, developers therefore require information derived from different analytic techniques to understand design systems.

Previous research has demonstrated how the tools and context are integral to the organisation of design work and the importance of considering these when providing technology to support collaboration in the design process. However, to begin to understand the mechanisms involved in co-ordinating design work and their relationship to context, a framework or theory is required to link the component parts together. A range of approaches have been adapted and developed in pursuit of this ideal that might allow the analysis of design and designers, and which can account for more than the individual cognitive properties of the designers themselves.

### 2.3.2 Moving out of the lab: the systems approach to task analysis

A growing number of influential researchers, (e.g. Vygotsky, 1978; Bannon and Bødker, 1991; Carroll, 1993; Zhang and Norman, 1994; Hutchins 1995a) have moved away from purely psychological studies of mental activity in human activity. They claim that an approach biased towards the agency of 'mind' is flawed in our understanding of human behaviour, because the world is full of stimuli, interacting with each other, placing demands on people that are not experienced in the laboratory. They conclude that whilst laboratory studies may well be important in understanding the lower, more basic functions of the brain, they have been singularly unsuccessful in informing scientists about human behaviour in the real world.

The modern tradition of psychology, especially the cognitive experimental variant that has achieved particular prominence in the last 30 years, has failed to deal effectively with 'real world' cognitive activity. The current research paradigm attempts to consider a single variable in a situation, by performing experiments that alter the parameters of that variable within a laboratory setting. However, humans do not exist in such a resource limited world: we rarely perform behaviours that are not mediated through the use of tools or that exist outside complex and informationally rich environments. Whilst experimentalists attempt to map out an architecture for individual cognition, they have failed to deal with the complex structure of the world and the real problems that people face in it - with a resultant loss of ecological validity (Neisser, 1967). Through simplifying the problem to a manageable level of detail, the experimental approach disallows the study of behaviour within complex and unpredictable environments in which multiple resources for action may be selected.

Cognitive models of human activity fail because of their focus on the individual, whilst real world activity is situated within a context and often in a highly complex environment that cannot be forced into the limited set of behavioural categories that cognitive modelling demands. One particular problem that the cognitive approaches have failed to account for is the notion of 'user': with one person using a computer, this relationship is relatively simple. However, in work mediated through socially organised activities, the user is a much more elusive concept. Within an organisational context, is the user the person who performs the task, or the person who the completed task is passed on to? In a multi-user environment, such as a video-conferencing or email system, are they the conglomerate of all of the users, or should the analyst consider the individual perspectives of all of the participants? A grain of analysis based on the individual cannot deal with the complexities of CSCW systems, and other approaches that can deal with these issues have moved to centre stage.

Traditionally in HCI, a micro-structural analysis of behaviour was considered to be the appropriate grain of analysis for developing computer interfaces. The cognitive paradigm and the information processing approach (Newell and Simon, 1972) was initially adapted to examine an individual's behaviour as problem solving, in terms of the problem structure of the activity. Task analyses (Johnson, 1992) were developed to break down the structure of activities into their component parts, often down to reaction times, such as the GOMS and Keystroke Level Models (Card, Moran and Newell, 1983). A range of such techniques, including variants on GOMS (e.g. Kieras, 1991), and task action grammars (Payne, 1984), amongst others were developed, but despite the early promises of such work, these methods have never been integrated into mainstream (i.e. academic or non-critical) systems design (Johnson, 1989). A fundamental problem with these forms of analysis was that they fail to take account of the larger task that such molecular activities are embedded within. The task analyses also focuses on the knowledge held by users about the system, and do not account for resources in the environment that are used to organise behaviour. Only recently have approaches been made to counter these criticisms of task analysis, although they are at an early stage of development and are largely theoretical at present (van der Veer, Lenting and Bergevoet, 1996; van der Veer, Hoeve and Lenting, 1997).

The gradual acknowledgement that a 'micro-structural task based analysis' did not consider the global task that such micro-level activities were embedded within has led researchers towards a greater consideration for artefact centred, contextual and organisational studies of activity more concerned with ecological validity than these early approaches. These 'ecological' approaches are particularly appropriate for the study of engineering design because of the nature of the design process, which operates in an environment rich in organising resources, such as tools, other people and a structured approach to problem solving. Ecologically valid research considers the work *system* as a whole and has more to offer systems design in generating appropriate (i.e. useful and usable) recommendations for technology to support design activities within a setting than the smaller granularity task-analyses.

A systems view (Norman, 1991; Zhang, 1992; Green, Davies and Gilmore, 1996) of design, with its focus on interactions between the artefacts and the human cognitive elements offers a more appropriate, higher level of analysis. In this systems perspective, it is the system, rather than the cognitive properties of the individual or the design of the artefact that determines overall performance at the task. Problem solving is distributed between the mind and the mediating structures of the world (Simon, 1981), and the systems view takes an approach to the analysis of design that considers all of the factors encompassing the process.

### 2.3.3 Ecological, contextual and situated approaches to systems analysis

An important change in psychology on the role of artefacts in the world on cognition was the concept of the 'affordance' developed by Gibson (1979), who proposed that people used features in the world to structure their ongoing activities. This 'ecological' approach to psychology linked perception and action through objects in the world that 'afforded' certain forms of use. Affordances were proposed as a method by which people could interact with their environments without the need for internal representations of the world (Norman, 1988). Gaver (1991) further developed the notion of the affordance being shaped by culture and experience.

Other influences of the systems approach to human activity were the Soviet cultural-historical psychologists (Vygotsky, 1978; Luria, 1979) who moved the study of psychology away from the examination of cognitive resources in the mind of the individual to the social, situational and cultural resources available in the world around the individual - tools, language, other people, and the division of labour that formed the 'functional system' of activity. This was also recognised by Wundt, one of the forefathers of scientific psychology, who placed great emphasis on the role of 'historically accumulated, culturally organised knowledge' in behaviour (Cole and Engeström, 1993). This cultural-historical knowledge cannot be explored with the experimental method, and has therefore been largely ignored in mainstream psychology.

More recently, research into situated cognition (Lave, 1988; Henninger, Lemke and Reeves, 1991, Agre, 1993) has embraced an anthropological approach to examining cognitive activity; like the Soviet psychologists, the claim is made that:

> "Cognition" is seamlessly distributed across persons activity and setting...thought (embodied and enacted) is situated in socially and culturally structured time and space (Lave, 1988, p.171).

To Lave, the unit of analysis should not be those of cognition or culture, but that of 'activity-in-setting'. She goes further and states that the environment cannot be simply considered as a resource for consulting (for example, as a memory), but as an active resource in achieving the system goal, allowing cognition to be stretched over mind, body, activity and setting.

Although a significant amount of research has already been carried out into the area of communication, co-operation and collaboration (sections 2.2.4 and 2.2.5), there is only a certain amount that we can learn from such abstract understandings - because behaviour is highly situated and context dependent - and generalised theories of collaborative behaviour are unable to answer all questions across these different settings. Indeed it has been argued that modelling co-operative work for CSCW systems cannot provide useful insights for the reason that activity is contingent on its highly variable circumstances (Suchman, 1987; Schmidt, 1991). However, this strong stance is not taken in this thesis, and its implications should reach outside the domain of engineering design in construction and speak to other research areas, because although collaborative design has some unique features, it is a subset of work in general, and the findings may be broadly applicable to other areas of activity.

To build usable computer based systems (or new work systems of any kind), an analysis must take into account the social nature of work in the system, the tools used in it, and the context that this work occurs within. The development of the systems approach to understanding human activity has drawn from a number of intellectual traditions, although the area has only recently achieved a high level of prominence. These areas are elaborated on below, setting the background to the methods that will be used to examine the organisation of collaborative design activity in this thesis.

## 2.4 Extending the boundaries of cognition

### 2.4.1 Theoretical approaches

Why do we need a theoretical approach? Why does the research need to be structured within a framework? These are quite reasonable questions that might be asked by software engineers and systems developers. The answer to such questions is that with a problem area as diverse and complex as collaborative design, theory provides a background with which to frame the problem, to pose questions, to analyse, to describe and to explain the results (Rogers, Bannon and Button, 1994). Without a theory to structure the data, interpretation of its underlying form is not possible, and the data collected may be meaningless.

The theory to apply in the analysis of the data collected requires a great deal of consideration. The failure of the existing information processing model of human cognition to deal with the issues of "context" raised by HCI and CSCW, the renewed interest in the role of artefacts in human activity, and the role of social interactions in creating meaning determines the form of theory that will be needed to conduct analyses of complex activity systems. The theory chosen must deal with these issues if it is to be a serious contender in identifying areas relevant to systems design. This has led CSCW researchers to adopt the theories and techniques of social science in an attempt to integrate these issues in order to investigate work from a systems perspective.

In applying the methods of social science to inform systems design, CSCW researchers have encountered a problem, because their techniques were not originally developed as applied disciplines. In particular, the techniques associated with the theories used in CSCW must be able to adequately identify, describe and analyse the relevant aspects of work activities to inform systems development. Relevance to developers was not a central concern during the historical development of most social science disciplines. Systems developers also require information in a very different form to that which social scientists usually provide, which tend to be lengthy reports that deal with a vast range of issues and covering a multitude of areas that the developers may or may not be equipped to provide support for. These reports tend to be descriptive results rather than providing the prescriptive information that developers expect and require to build new systems.

The interdisciplinary techniques used by social scientists involved in CSCW have attempted to deal with these problems, with varying degrees of success. An early naive approach in the design of collaborative technology was that social science would provide a framework for understanding human activities which could be directly translated into guidelines for design; however, the mapping of behaviour patterns directly to systems redesign (particularly through the introduction of technology) has been largely unsuccessful, and CSCW researchers are now looking for other interfaces between social science and systems development.

Some interesting theoretical approaches that could be applied to the domain of CSCW and CSCD are outlined below, and summarised in table 2.1 at the end of the section. It must be stressed that these are all evolving frameworks (Nardi, 1992) and are constantly engaged in cross fertilisation, drawing inspiration from the others. In addition, the different theorists who have come up with these theoretical categories do not always agree with each other on the minutiae of the frameworks.

### 2.4.2 Activity theory

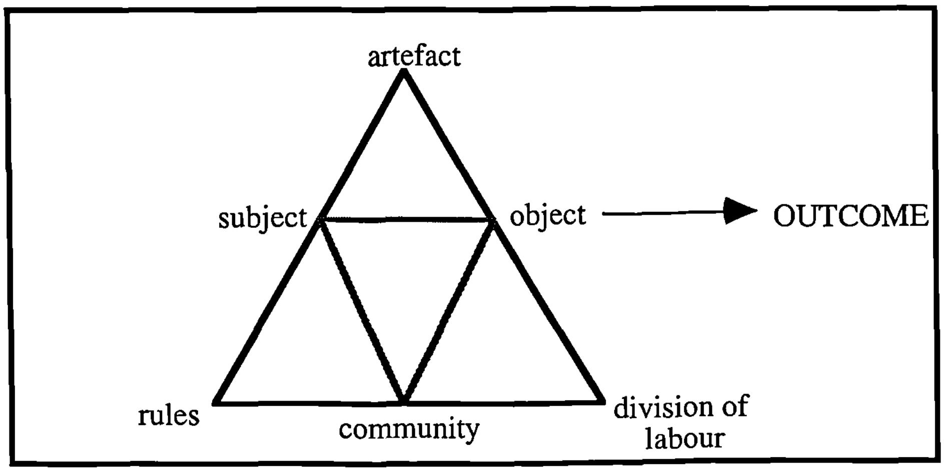
Activity theory (AT) is a relatively recent area of research in the field of HCI and CSCW (Nardi, 1992; Bødker, 1991, Kuutti, 1990; 1991; Aboulafia, 1994). Its adherents claim that it provides a framework for multi-disciplinary research, allowing researchers to link different types of information within a unifying framework (Kuutti, 1991). In AT, the technical, social and cognitive aspects of work are all considered as components that contribute to the unit of analysis, the *activity*.

Social interaction and the artefacts that mediate it (tools and words), are seen as central to mental thought in activity theory. Activity (corresponding to the cognitive psychological term, 'task') is distributed over people and the technical tools (computers being highly adaptive tools) which mediate activity[4]. Hypotheses are generated about specific factors and studies can be set up to test these at a more specific level of analysis (Aboulafia, 1994) using descriptive methods to study them.

The AT framework allows researchers to structure the component parts of an activity into several dimensions; along the primary entities of subject (human actor), object (something or things to be transformed through the activity) and tool (or artefact, mediating the relationship between subject and object). Yrjö Engström (Cole and Engström, 1993) develops this further by adding another unit, the 'community' (others engaged in the activity), that can mediate activity in a different way to the 'tool'. Interaction between the subject and the community is mediated by social rules, and between the community and the object of activity, through the division of labour. This is shown graphically in fig. 2.1. (ibid. 1991, p. 257).

[4] Suggesting that it is not just the tools that can be redesigned (the traditional HCI approach) but the whole of the work activity, including its content and organisational structure.

Fig. 2.1. Mediation of activity in Activity Theory




Using an example of knitting (following Boden's [1977] use of a gender reversed example[5]) a description of activity in an AT framework would consider the knitter as the subject, the needles and the properties of the wool as tools, and the wool itself as the object, when transformed into a pullover. Using knowledge drawn from the community, transmitted through the rules of interaction, the subject could have learnt to knit and gathered patterns to use. If there were several knitters, the community could be organised to knit the sleeves, the body and other subcomponents through the division of their labour. Thus, the activity, encompassing several forms of behaviours, can be broken into segments that can be analysed separately, using appropriate techniques for the unitary components.

This arrangement of entities provides a means of breaking down the activity into smaller, well defined constituent parts, each of which can be examined either alone, or through the relationships between the components. This structured approach gives a structure to the descriptions of social interaction that many other methods do not express; however, as yet, despite its apparent potential, the framework has not been used extensively within either CSCW or systems design. It has also been criticised, even by its proponents (e.g. Kuutti, 1990) for being overcomplicated, slow and difficult to use.

### 2.4.3 Cognitive sociology and the ethnomethodological approach

Sociology is concerned with the nature of work and social organisation, and in essence, this is what this thesis attempts to examine in groups of designers. However, its concerns are typically with society at large, not groups, and thus it appears to contribute little to the development of CSCW technology. Nevertheless, sociology,

[5] The all too obvious cliché being the description of driving a car.

and in particular, one variant of sociology has been adapted to the study of collaborative work.

One of the central premises of sociology is that all activity is social in nature (Schmidt, 1991): it is situated within a social context, mediated by social pressures and learned in a social milieu. Work is a social activity, with goals and operations defined by the social context that individuals are immersed in. One particular group of sociologists - the ethnomethodologists - have dominated the study of the social organisation of work. Ethnomethodology is a variant of sociology that has come to be the dominant paradigm of analysis in CSCW, and inspired a large body of research papers in the area (e.g. Heath and Luff, 1991; Heath, *et al*, 1993; Randall and Hughes, 1995; Bowers, Button and Sharrock, 1995). Ethnomethodologists seek to try to understand how work activities are ordered through the process of interaction, and the approach has achieved a respectable position in CSCW in examining the social organisation of work.

One particular insight that the ethnomethodologists have provided is that they have begun to uncover the details of how work is performed, rather than the decontextualised 'examples' (Randall and Hughes, 1995) of work that traditional sociology describes as background material for analyses (Sharrock and Anderson, 1986); such decontextualised studies lose important understandings about how the structure of the work itself might interrelate with the organisation of the people performing it and the technology that they use.

A derivative of the ethnomethodological approach is situated action (SA) which has been developed particularly with human-machine interaction in mind. Rather than concerning itself with the social nature of work, it concentrates on other aspects of the situation that work exists within. Like ethnomethodology, it posits no deep structure on activity. Suchman (1987) contrasts situated action against cognitivism and artificial intelligence by rejecting internal representations as irredeemably decontextualised (disputed by Vera and Simon, 1993), denying a causal role for the goals and plans that the psychological sciences use to explain behaviour. Instead, the organisation of the environment is argued as central to actions performed in it, emphasising the emergent, contingent nature of activity (Nardi, 1992).

Suchman's (1987) 'Plans and Situated Actions' has been the driving force behind much of the research into the role of context in activity. Cognitive plans, she argues are the result of *ad hoc* interpretations of actions in the world, although they are also used as resources for actions. Actions, driven by situations, are a focal point for the SA theorists in understanding the organisation of work. The resources that people use are opportunistically selected from those at hand, rather than driven through forward planning. Hence, the organisation of problem solving activity is emergent and situated in the environment in which the actor finds themselves:

> '...the organisation of situated action is an emergent property of moment-by-moment interactions between actors, and between actors and the environments of their action.'
> (Suchman, 1987, p. 179)

To summarise, the method used by ethnomethodologically informed researchers involves an analysis of the social interaction of individuals collaborating in their activities. Their focus is firmly on language, with close links to 'conversation analysis' (Cicourel, 1975). However, cognitive sociology fails to directly incorporate the use of common objects (section 2.2.4) into their analyses. Another problem in using ethnomethodological research in CSCW is that it takes a largely atheoretical approach to analysis, involving often long descriptions of activity as observed. They do not attempt to provide a theoretical basis for their findings (for philosophical reasons), and claim that 'the data speaks for itself', which does not lend itself easily to supporting the work of systems developers.

### 2.4.4 Situated cognition and distributed representations

Situated cognition (SC) is an approach that seeks to describe cognitive activity rooted within a physical and social context (Zhang and Norman, 1994). Like situated action, the SC perspective views activity as emergent, drawing from, and structured by, the resources available in the setting. However, SC is concerned with cognitive processes and the external representations in the world that are used to support actions in the pursuit of a goal - cognitive terms that situated action avoids. As with activity theory, SC considers the activity to be the fundamental unit of analysis.

Theories of distributed representations (Zhang and Norman, 1994; Zhang, 1990) and external representations (Woods and Roth, 1988; Larkin, 1989; Larkin and Simon, 1987; Vera and Simon, 1993) fall squarely into traditional cognitive science, in which tasks are decomposed into different forms of representations, and where '*the representation of the world provided to a problem solver can affect his/her/its problem solving performance*' (Woods and Roth, 1988. p. 26). These theories posit two forms of representations, internal (in the mind, either serial or connectionist), and external (in the world, as physical symbols), which are combined into an abstract task space during problem solving activity. Through using representations available in the world, cognitive actors do not need to maintain complex mental representations. Perceptual information performs part of the cognitive task, and external representations become a component part of the human cognitive system. The physical constraints on activity that these external representations bring to cognition are important in reducing the rule base required to comprehend the world (Zhang, 1990), simplifying the task at hand, and fundamentally changing the nature of the task from one that is solely mentally represented (Zhang and Norman, 1994).

Essentially, for the distributed representation approaches, parts of the cognitive system knowledge can be carried in things such as numeric systems (Zhang and Norman, unpublished) or databases. These representational systems extend the symbol manipulation capabilities of the unaided human mind beyond that which they could accomplish without these artefacts. The situated properties of cognition (drawing from social and physical resources present in settings) allow us to sometimes avoid mental symbol manipulations (Zhang and Norman, 1994; Pea, 1993; Vera and Simon, 1993), and to use the representation to take the load of the information processing requirement.

In design, there are often many possible ways to solve a problem through the way that it is represented (problem isomorphs - Khaney, 1993), because there are many possible solutions. For each of these solutions, there are many intermediate pathways that can be followed. For example, engineering calculations can be done mentally, using a pen and paper, using a calculator or using specialist CAD software. Different problem isomorphs have different cognitive characteristics and place different cognitive loads on the agents performing the task. Designing systems to support collaborative design therefore requires identification of the problem isomorphs that appear the most 'natural' to the users, and that best carry the communication to co-ordinate the designers in the system.

SC and distributed representation theories take Simon's (1981) notion of the human as a mundane processor of information to its logical conclusion through using situations as practical resources for thought. This is performed through breaking the boundaries between perception and cognition (Butterworth, 1992), as perceptual mechanisms are incorporated into information processing. However, so far, the distributed representation approach has only involved single individuals, rather than social groupings (although see Zhang, unpublished), it is possible to see how the world and artefacts in it can be augmented through the addition of other actors in a social context. However, such research is not informative about the social and organisational mechanisms of co-ordination, because of its preoccupation with determining the locus of the representation (i.e. internal or external) rather than their organisation in the performance of the task.

Table 2.1. Approaches for examining collaborative systems.

| Approaches | Summary | Limitations | References |
|---|---|---|---|
| Activity theory | Unifying framework for cognitive, social, organisational and technological components of activity. Action mediated by artefacts and community, so has potential for application in CSCW. | Awkwardly adapted to CSCW. Overcomplicated, slow and difficult to use. Few examples of use in CSCW. | Nardi, 1992; Bødker, 1991; Kuutti, 1990, 1991; Aboulafia, 1994; Vygotski, 1978; Luria, 1979; Cole & Engström, 1993 |
| Cognitive sociology and ethno-methodology | Activity is situated, mediated and learned in social context. Seeks to understand ordering of work through social interaction. Relevant to CSCW because interaction can change when mediated through technology. | Emphasis on language, not artefacts ignores organising features in environment. Descriptions overcomplex and leave much to interpretation. | Randall & Hughes, 1995; Bowers *et al*, 1995; Sharrock & Anderson, 1986; Cicourel, 1975; Heath & Luff (1991); Heath *et al*, 1993. |
| Situated action | Derived from ethno-methodological approach. Behaviour is emergent and opportunistic, not planned. Examines resources organising action. Developed specifically for CSCW. | Attention on opportunistic action - planning and rule following ignored. | Suchman, 1987, 1990, 1993; Suchman & Trigg, 1993; Nardi, 1992. |
| Situated cognition and distributed representations | Activity emergent and structured by resources in setting. Concern with external representations. Perceptual mechanisms incorporated into problem solving. Value to systems design in demonstrating representational organisation. | Focus on individuals in restricted domains. Fails to capture mechanisms of co-ordination in task performance. Oriented towards cognitive modelling. | Lave, 1988; Zhang & Norman, 1994, unpublished; Zhang, 1990; Woods & Roth, 1988; Larkin & Simon, 1987; Larkin, 1989. |

## 2.5 Computer support for collaborative design

### 2.5.1 Context, HCI and CSCW

The social sciences have been appropriated into systems development because they are able to capture the rich levels of detail about the enacted performance of work that formal methods of requirements analysis cannot (Jirotka and Goguen, 1994). This is described by Anderson (1994) in the quote below:

> "What the user is held to know about and to orient to in the daily routine of their workaday world is the practical management of organisational contingencies, the taken-for-granted, shared

> culture of the working environment, the hurly burly of social relations in the workplace, and the locally specific skills (e.g. the "know how" and "know what") required to perform any role or task. Formal methods of requirements capture, or so it is supposed are incapable of rendering these dimensions visible, let alone capturing them in the detail required to ensure that systems can take advantage of them." (p. 154).

However, having slated the formal approach to examining social and technical systems, other approaches are required to fill the vacuum. The different methods of analysing behaviour summarised in the previous section have all been suggested as answers to this. They can all be described as different worldviews on the descriptions given to, and explanations of activity (Agre, 1993), and whilst they may be underpinned with very dissimilar theoretical understandings, at a simplistic level, they express similar explanations about behaviour, and advocate similar, methodological approaches grounded in naturalistic research. Whilst each has different grains of analysis in which the cognitive element is lesser or greater, they move the problem solving element of behaviour away from the neurological conception of 'mind'. Many of these approaches have arisen independently, but carry the same underlying ideas, whilst they can also differ significantly. Often these differences have arisen because of the different academic backgrounds of the theorists and the different problem areas and grains of analysis that the practitioners are wrestling with.

All of the approaches described above take a different perspective to that traditionally taken in HCI (Clegg, 1994), moving research away from an emphasis on the study of human behaviour as rational, planned and individually centred. Within the field of CSCW, where social and organisational behaviours are central issues, experimental and individual-centred approaches have failed to provide practical help in the design of useful and usable systems. Novel approaches that emphasise the role of context in behaviour, have risen to the fore and have contributed to a new understanding of behaviour, considering it as an emergent, rather than pre-determined activity, that arises through factors both internal and external to the individual.

### 2.5.2 Designing artefacts for collaboration

The development of technological artefacts has generally involved the computerisation of existing artefacts, for example, CAD replacing the drawing table in design. However, replacing the artefacts of work is not a simple matter of replacing one object with another, because artefacts have been designed and adapted to their use over time. It is therefore important when replacing old technologies, that artefacts should be examined in their contexts of their use (Bannon and Bødker, 1991) to see *how* they are used in the performance of work. The reason for this is that artefacts are often perceived to have a single function whilst they in fact support a number of non-obvious activities (Brown and Duguid, 1994; Robinson, 1993a). When considering redesign of an artefact, it is necessary to consider these contextual factors.

The relationship between context and systems design is considered in a special issue of the Journal of Human-Computer Interaction (Ed. Moran, 1994). In this issue, Brown and Duguid (1994) argue that the context of work is central to the co-ordination of that work, and what the users understand about the context must be understood when redesigning this work with technology. Artefacts are used as objects of co-ordination, because some features of these artefacts (the 'border resources') are used to mediate relations between co-workers. Indeed, there is a natural tendency for people to share tools, even when they are designed for personal use (O'Day, 1994). The social and work related nature of these artefacts are interwoven, and are hard to pare apart - changing the artefact could seriously impair the ability of groups to co-ordinate their activities.

CSCW needs to do more than theorise about the social organisation of work. It must also help inform developers about how to support the various divisions of labour that workers operate in (Bannon and Harper, 1991). In redesigning technology, and therefore redesigning work itself, technologists may remove seemingly anachronistic practices which may in fact have important co-ordination functions in the collaborative processes (Halverson, 1994). These are the 'borderline issues' (Brown and Duguid, 1994) where 'task non-essential' details are utilised to co-ordinate behaviour. CSCW must provide support for the development of appropriate technology by uncovering these border resources.

System designers need to have a better understanding of how humans act in their work environments to develop useful and usable tools, appropriate to that environment. Whereas Simon and the psycho-cognitivists consider problems as objectively existing, with initial states, goal states and operators, the more contextually aware disciplines view problems only in relation to actors and their environments. Context is a resource in design, possibly the dominant one, and must be taken into account (Henninger *et al*, 1991) in developing an understanding of the design activity.

### 2.5.3 Collaboration, technology and theories of design

A deep understanding of design to support the development of technology needs to take account of the culturally constituted and other situationally dependent contingencies that form the basis of real design problems. Building technology is not enough - we need to learn more about how groups, organisations and technology are organised. However, few researchers appear to have examined the design process as a whole. Design has been shown to be an iterative process, where research that concentrates on a particular component of the process neglects the whole, and failure to attend to the situation as a whole devalues such studies for their application in CSCW and CSCD. Of course, much of this limited understanding the design process has developed from the concerns of disciplines different to those of CSCW, and so do not attempt to capture these elements. As an emerging area of research, CSCW must not simply adapt research from other areas but develop its own techniques and theories so that it can make a real and discernible contribution to the development of effective collaborative technology.

The approaches described above have some of the features that research into CSCW requires to tackle in informing systems design. However, none of the approaches links all of the features of work activity (cognitive, social, situated, and mediated by artefacts) into a unified whole that can be directly applied to the analysis of collaborative design, which must integrate the social and organisational aspects of work with the objects involved in that activity and the problem solving nature of design work. This involves an integration of several disciplines which interweave the social and cognitive components of activity, the results of which must be in a form that can be used to inform the design of technology. A branch of cognitive science has been recently developed up that is attempting to seriously tackle these interdisciplinary issues. It is known as 'distributed cognition'.

## 2.6 Summary

This chapter brings together current understandings about the component parts of the problem under examination: collaboration, design, methods for examining collaborative work, and their relationships to systems development. Current work on design is discussed, demonstrating how cognitive approaches have failed to explain the collaborative design process in settings supported with a range of physical and organisational resources. These current understandings about design do not describe the social and situated nature of activity well enough to develop technology to support design work, and new theories and analytic techniques are therefore required. Techniques based on the social sciences are discussed and compared as a means of making explicit the mechanisms used to co-ordinate activity. The issues that these techniques raise for HCI and CSCW are explored. The chapter concludes that another approach, that of 'distributed cognition' is best suited to describe the collaborative design process in the context of systems development. This is described in the following chapter.

# Chapter 3

# Distributed Cognition in Collaborative Systems

> *'Traditionally, human cognition has been seen as existing solely "inside" a person's head, and studies on cognition have by and large disregarded the social, physical, and artifactual surroundings in which cognition takes place' (Salomon, 1993).*

## 3.1 Overview

This chapter outlines a distributed cognitive framework to enable the examination of work systems within settings. The framework focuses on the representations involved in information processing because access to the representations involved in activity allows analysts to determine the *resources* used in the performance of problem solving, and consequently, design. Artefacts are the physical embodiments of representations, and the media through which representations are operated upon in the world. Understanding the role of representations and the processes involved in transforming them will therefore give an insight into the nature of the resources used to perform collaborative work and design. The chapter discusses how representations, and the processes that are involved in transforming them, are used in cognitive activity that is distributed over collaborative systems. To support this theoretical analysis of collaborative work, a method for collecting data on distributed work systems is described and modified to focus on the representations and processes used.

## 3.2 Cognition in the world

As the quote at the beginning of the chapter illustrates, the study of behaviour has been dominated by a psychological perspective on the cognitive sciences. The search to uncover the fundamental processes behind behaviour has concentrated on human mental capabilities and attempts to formulate an architecture of cognition (Anderson, 1983; Newell, 1990). In doing so, the sub-disciplines of cognitive science have been sidelined, in particular, anthropology, de-emphasising the roles of context, culture and history (Gardner, 1985), in favour of a stance focused on unsupported mental processes as the main determinant of activity. The development of computer systems to support human performance in the workplace has provided an impetus for re-examining this stance, because in these settings, individual cognitive effort is only of use when integrated with those of others. This has led to the development of an approach to the study of problem solving and collaboration that can account for the situations that such activities take place in and the resources that are available to the actors. The switch of attention towards the resources external to the mind has moved the study of cognition out of the laboratory and into the world (Norman, 1993), and this radical departure from the traditional understanding of cognition is critical to the position taken in this thesis.

Humans have the ability to not only use information in their environments, but also to create tools, or artefacts - man made or modified objects (Cole, 1990). Tools to aid cognition are known as 'cognitive artefacts' (Payne, 1992 - also section 2.2). Cognitive artefacts include external representations of knowledge in the world as memory aids ('knowledge in the world - Norman, 1988), such as checklists and books. They are also used to augment human cognitive abilities, and include devices such as numeric systems (Zhang, 1992), computational devices such as slide rules or calculators, or a combination of both. By performing simple manipulations on cognitive artefacts, humans can logically process information without performing logic operations in their heads (Rumelhart *et al*, 1986a). A fundamental feature of cognitive artefacts is that they do not simply augment existing human capabilities, rather, they transform the task into a different one (Cole, 1990; Norman, 1993), allowing resources to be reallocated into a configuration that better suits the cognitive capabilities of the problem solver.

Cognitive artefacts do not simply support the cognitive processes of individuals (Norman, 1991a), and an example of this is language. Language is a particular form of cognitive artefact (Cole, 1990), that allows humans to spread their cognitive load over a group of people, changing the task from an individual cognitive problem to a distributed problem dispersed over social space.

Expanding the focus of cognitive activity away from the unsupported individual towards a system of tools and groups of people is a far more appropriate unit of analysis if we are to study a real world activity such as collaborative design. Several methods of analysis, discussed in the previous chapter, have been developed to analyse activities involving such multi-tool, multi-participant behaviour. However, none of them are fully appropriate for the study of what is still fundamentally a *cognitive* problem which involves a problem solving approach to be applied by the agents involved. Problem solving involves a system traversing a 'problem space', by moving through various transitory states towards a goal: these problem states are representational in nature, and analysis must therefore focus on these representational states. One method that makes explicit the cognitive paradigm in this enlarged domain of study is distributed cognition.

Analyses with a distributed cognitive framework have been used to examine the cognitive properties of airline cockpits (Hutchins and Klausen, 1990; Hutchins, 1995b, unpublished), the navigation systems of naval vessels (Hutchins, 1988; 1995a), air traffic control operations (Halverson, 1994, 1995), shared CAD systems (Rogers, 1993), shared database systems (Nardi and Miller, 1989), collaboration between programmers (Flor and Hutchins, 1992), and a fishing community (Hazelhurst, 1994), amongst others. This approach to examining the cognitive properties of multiparticipant systems has a great deal of potential for identifying how such systems act as processors of information. To support such activity systems with novel technology, an understanding their information processing requirements and processes is vital in pinpointing where the application of collaboration technology could both benefit work and be implemented without disrupting activity through removing the resources used in co-ordination (Brown and Duguid, 1994; Halverson, 1994). When developing new systems that involve the transformation of work practices, this second point about maintaining the resources used in co-ordination may be as critical as that of proposing novel technologies. Such an understanding allows developers to determine where change should not occur, and where it does, by providing new media that simulate the function of the original co-ordination resources (see also section 2.5.2).

## 3.3 Cognition as a social phenomenon

### 3.3.1 Definitions of cognition

There has long been a debate as to what thought involves, a particularly pertinent example of which is Descartes' mind-body separation in the theory of dualism. 'Cognition', as we know it today, is a more recent innovation, achieving prominence in the 1950's and 1960's (Gardner, 1985), nd is separated from the much harder to quantify conceptions of mind, involving consciousness, qualia and affect. Initially, cognition was assumed to be a mental activity, and its earliest proponents such as Neisser (1967) and Simon and Newell (1972) wrote about it as involving single individuals. Neisser (ibid.) defined cognition as referring 'to all of the processes by which the sensory input is transformed, reduced, stored, recovered, and used'. The focus of such studies into cognition, or 'cognitive science', were located in the realms of problem solving. Descriptions of cognition thus considered the abstract machinery of problem solving and the organisation of knowledge about the problem domain (knowledge representation).

According to information processing theory (Newell and Simon, 1972), problem spaces (the representation of the operations required for a given task) are abstract representations, and as such are not restricted to a single individual locus. Indeed, Neisser's above definition of cognition does not delineate who, or what architecture, the cognition should be implemented in. Problem solving does not therefore have to be performed by an unaided individual: any unit performing these activities could be described as a cognitive entity. Individuals can use elements of their environment in cognition, but perhaps most powerfully, groups of people, using artefacts in their environment could be described in terms of the cognitive paradigm.

Work is not normally performed unaided and alone, and the social aspect to problem solving is recognised by Sproull and Kiesler (1991), who argue that 'the fundamental unit of work in the modern organisation is the group, not the individual', and that many of the important aspects of work are 'organised in departments, sub-units, committees, task forces and panels' (p.25). Problem solving behaviour in work activities must involve a unit greater than that of the individual, who becomes a component of the group's problem solving resources. To study a smaller unit of work than the group will miss many important features of the work where problem solving is distributed over a network of individuals co-operating with one another to achieve a solution. Whilst processing of the information available to the group is analogous to an individual's cognitive capabilities, the architecture of this activity differs because of the different representational properties of the resources available. Here, the knowledge base built up by the psychological sciences is less useful in the analysis of problem solving performance for the extended unit of cognition.

### 3.3.2 Cognition, representation and communication

Distributing work across a group of agents must involve the organisation of that group to co-ordinate activity through some form of communication. In his study of navigation, Hutchins (1995a) describes the hierarchical system of naval rank and the roles that these individuals are expected to play in the navigational fix taking cycle. He documents the representations that communications are encoded in, and how the combination of all of the interacting parts of the system operate to process information to achieve the navigational system's goal (locating the ship in two dimensional space). At no stage in the process can a single person be said to be navigating the ship, which occurs as an emergent property of the individual behaviours of the navigation team. Although the process is not controlled by one person, the performance of the system is not entirely random: individuals are assigned responsibilities and perform roles determined through the prior organisation of work.

The 'systems' based perspective on activity needs to describe all of the features that are present in the system: people, artefacts and most importantly, the means of organising these into a useful unit. We therefore have a cognitive system[1] that is mediated through the expression of features arising through non-neurological mechanisms - a system of socially distributed cognition (Hutchins, 1995a). Socially distributed cognition describes group activity in the way that individual cognition has traditionally been described - computation realised through the creation, transformation and propagation of representational states (Simon, 1981; Hutchins, 1995a).

Communication occurs through the transmission of representations (or symbols) on cognitive artefacts between agents. Language is an example of this: it enables the encoding of a (mental) representation that can be transmitted between agents through the medium of speech. Commonly accessible, physical cognitive artefacts are also used as a medium for communication within systems, although they may not explicitly be used as communicative devices. Thus, drawings created for individual use may have a communicative function. For the communication medium (the cognitive artefact) to be used in problem solving behaviour by the distributed cognitive system, the representation encoding the information must have a universally understood meaning between the sender and recipient. Universal comprehension of the medium may derive from common experience, training, or through its use in the setting. This meaning (or mapping) may be self evident, mirroring features of the environment, such as a picture (analogue representations - Woods and Roth, 1988), or they may be more abstract and complex, like text, which require transformational rules for interpretation. Precisely what form these representations take will be determined by the situation that the activity is carried out in, because behaviour is dependant on the resources at hand in the setting, as demonstrated by Suchman (1987). Where there is a choice of representational media, one or more of these media will be selected from those available, the choice of which will be dependant on criteria such as past experience with the artefact and appropriateness to the situation.

[1] It is a cognitive system because it exhibits 'intelligent', purposeful behaviours in problem solving and information processing.

Language is an important resource for communication, either spoken or written[2]; however, it is not always the most appropriate medium of representation. In some instances, other representational forms may be more appropriate for communicating information through the system, examples of which may include charts, graphs or drawings. Language is used in combination with other representational media, which provide an indexical focus (something to look and point at) in conversation. A physical artefact can also provide an enduring record of the communicative event to refer back to at a later time, a feature that speech fails to capture. Language is therefore not the only representation carrying communication mechanism that should be examined in the study of communication. Other representational media are equally important in examining communications within socially mediated cognitive systems, particularly ones that operate in media rich environments, and where agents within the system are widely distributed over several distant locations.

## 3.4 Distributing Cognition

### 3.4.1 Rationale and aims of distributed cognition

Distributed Cognition (DC) provides a means of describing how the structure of the world, embodied in artefacts and the situational context, imposes *constraints* on the behaviour of the extended cognitive system (comprising of multiple agents within an informationally rich context). The form of distributed cognition advanced by Hutchins is explicitly aimed towards the re-development of systems through their technological media and internal organisational (Flor and Hutchins, 1992; Rogers and Ellis, 1994) to better take advantage of human capabilities and provide support for their limitations. Its goal is to extract information that system designers require in order to make better informed judgements about the information processing requirements of systems of collaborating agents. DC analyses achieve this through deriving the external symbol system (Newell and Simon, 1981) that captures the elements of processing (representations and processes) that transform system inputs into outputs for particular tasks.

There are a number of variants on distributed cognition, ranging from versions where cognition is used as a *metaphor* for understanding group behaviour (Nickerson 1993; Pea, 1993), to versions where the elements of the work system act as a *physical architecture* for cognitive processing, such as that advocated by Hutchins (1995a,b).

[2] Language is a critical component of communication; however, to do it justice, it would require a great deal more effort than can be provided within this thesis, which limits itself to the propagation of representations across multiple media.

This thesis takes the second approach to distributed cognition. A distributed architecture for cognition allows the analyst to go beyond comparing the cognition of the group to that of the individual, which limits analysis to simple comparisons with the capabilities of individual humans. Examining the group as a computational system allows the analyst to examine the emergent behaviours generated through interactions between its component parts. It provides a unique insight into how technology and the socially generated media of communication act upon and transform representations, and in doing so, perform cognitive information processing activities.

### 3.4.2 Division of labour

Within the distributed cognitive system, problem solving and design expertise lies not only in the knowledge and skills of the individuals, but in the organisation of those individuals, through the configuration of the tools that they use and their work environment. The cognitive analyses of behaviour within a real world environment therefore no longer requires the examination of an individual's psychological functions, but must examine the larger unit and develop new analytic methods to determine how cognition is distributed socially, spatially, materially, and even over time (Cole and Engeström, 1993).

Whilst the structure of the environment is important in determining action (Suchman, 1987), actors do not passively adapt to existing structures. DC theorists (Hutchins, 1995a; Hazelhurst, 1994) claim that the proactive *structuring* of work activity is central to organising and co-ordinating the actions of collaborating individuals. Groups continuously structure their environments through their actions as they perform work. This structuring involves organising and reorganising the physical and cognitive artefacts in the environment, and generating and transforming the social context that the behaviours on these artefacts occur within. These organising structures are retained as representations (either internal memories, or externally as written rules or checklists), or as constraints on behaviour (embodied in the physical artefacts and work environment). The structure of these constraints in the workplace[3] therefore plays a role in determining the architecture for the information processing activities of the functional unit.

The division of labour is a feature of human behaviour that enables our limited resources to spread out and cover an environment too rich in resources to be processed serially by a single actor. Thus, cognitive resources can be considered to be

[3] The architecture is formed from the microstructure of the environment that action occurs within. This in turn develops from macroscopic structures in the historical developments occurring prior to activity.

'shared' amongst several agents (Oatley, 1990; Hutchins, unpublished), which is the principle behind the division of labour. Tasks such as navigation and engineering design are carried out by multiple agents working together, and the division of their labour, in this case, is cognitive labour (Clegg, 1994; Hutchins, 1995a, unpublished). On large collaborative projects, people are often either assigned roles, or come to the project with existing roles (e.g. bankers or safety officers) which means that they have limited expertise across domains. The nature of this specialisation means that most, if not all workers will be illiterate in at least some areas of the collective task. However, they are able to interact productively with other specialists through the division of labour in a particular pattern.

Work activities may also be distributed over technological artefacts, and these too must be considered in determining how work is distributed. The organisation of this socially distributed (cognitive) labour will determine the system's performance on a task. If labour and tools are not organised effectively, the system's task may be performed slowly, incorrectly, or not at all. In shared problem solving, the collaborating agents must organise an effective distribution of labour to bring together their individual expertise to resolve their shared problem, and they must do this by communicating with each other. Understanding how this division of labour operates is central to our understanding of work organisation and working practices (Clegg, 1994). Developing CSCW tools to facilitate the co-ordination of collaborative activity in design will require the explication of the social processes that lie behind this division of labour so that they do not disrupt existing patterns of labour detrimentally.

Socially distributed cognitive labour will include activities such as planning, information gathering and processing, co-ordination activities and group cohesive maintenance, problem solving and decision making. This division of work over people and artefacts is known as articulation work (Strauss *et al*, 1985). As problems and situations evolve during performance of the task, articulation work must involve an ongoing division of labour (Randall and Rouncefield, 1995) that develops and changes to adapt to the situation. The tasks taken on by the agents may depend on a large number of factors including experience, skill, knowledge, training, location or occupation, and task allocation may be imposed, requested, assumed by or delegated to participants (Strauss, 1985). According to Strauss, the organisation of these elements is maintained by feedback in the form of reporting, where actions are monitored, evaluated and revised.

Despite the benefits in distributing labour across a number of agents, there are a number of costs associated with it. Effort and other resources must be put into organising the units that would otherwise have been available for the task, so there is a natural tendency to organise the systems to perform tasks with resource-inexpensive co-ordination activities. A shared understanding of the task and state of activity on the task is important in co-ordinating the division of labour - the greater the discrepancy in these shared processes, the greater the requirement for (more costly) explicit inter-agent co-ordination. In loosely organised systems, agents must be attentive to the work of others to organise the flow of work (Randall and Rouncefield, 1995) and to co-ordinate their collaborative activities. The physical layout of the task environment defines the distribution of access to information, and is therefore a major determinant in co-ordinating the ongoing division of labour (Hutchins, 1995a).

### 3.4.3 Inside the cognitive system

Cognitive science provides a useful frame of reference to examine intelligence, problem solving and other areas that are considered to form the basis of human intellect through examining the processes that organise human behaviour (Newell and Simon, 1972; Gardner, 1985; Hutchins, 1995b). Its does so through examining how information is represented within the cognitive system, and how these representations are transformed, combined and propagated through the system (Simon, 1981). The added benefit of examining cognition within systems larger than the brain is that many of the representations are directly visible and do not require the indirect methods of examination that experimental psychology has to use. In essence, the analyst can physically enter the cognitive system (Hutchins, 1995a) to see first-hand the representational activity within that system. However, some representations are invisible to examination, because they are located within the mental domain. In the case of distributed cognition, the level of granularity in the analysis is only concerned with the inputs and outputs to agents, and not their internal representations. This is true for the present study, which examines the co-ordination of work *between* agents.

The development of distributed cognition has drawn inspiration from the PDP - parallel distributed processing (Rumelhart and McClelland, 1986b), or connectionist approach to individual, neuronally based cognition, where the whole pattern of agent activation is the meaningful unit of analysis in cognitive behaviour, and the cognitive system is multiply connected and controlled. Important factors in the processing of information by the PDP system are the constraints of the task as well as that of the processor: there is no distinction between the information being processed and the information processing structures (Norman, 1986).

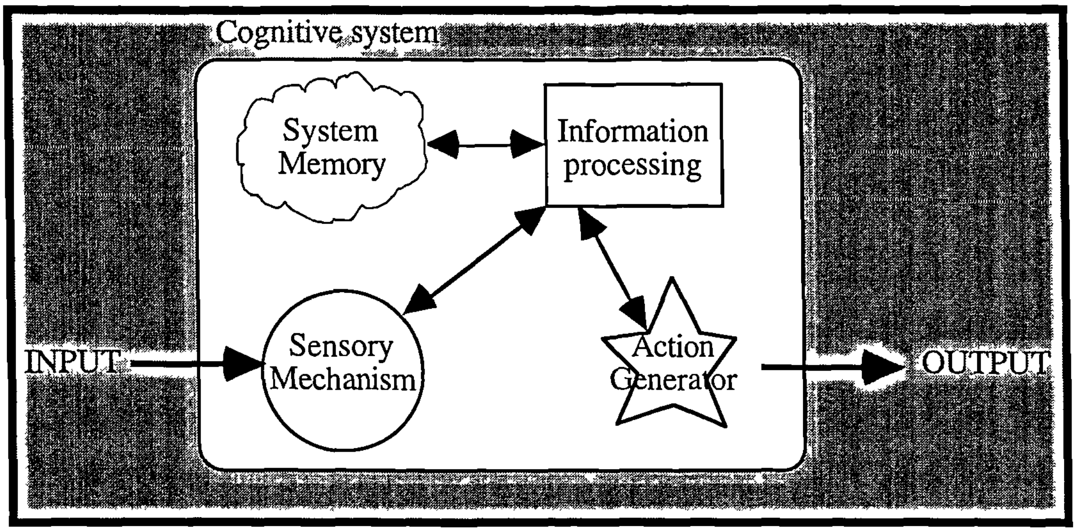
PDP systems are adaptive, configuring themselves to incoming data, and 'settling into solutions (Rumelhart *et al*, 1986b); in doing so, such a system 'exhibits intelligence and logic, yet...nowhere has explicit rules of intelligence or logic'

(Norman, 1986, p.537). This has close parallels to groups of individuals collaborating in a task. The difference that the DC system has to PDP, is that instead of using electrical or electrochemical interfaces between the processing units, it operates through socially mediated protocols between the units of the information processing system. Whilst systems of individuals are not as easily specified or homogenous as PDP systems, the PDP approach does show that self organising systems of information processors can work together to produce apparently intelligent and cognitively functioning systems. The distributed processing approach of both DC and PDP therefore entails a major rethinking of cognition, in which the intimate relationship between the psychological and social phenomena is a major feature (Norman, 1986b). As with the PDP systems, investigation of the (social) protocols that maintain and co-ordinate the individual processors is important in specifying the structure of the cognitive processor.

DC, as developed by Hutchins, has adapted the framework of individual cognition to explain how cognitive resources are organised *within a context,* drawing on actors and other features in the environment to perform problem solving. It is concerned with representational states and the informational flows around the media carrying these representations. The DC framework allows researchers to consider all of the factors relevant to the task, bringing together the people, the problem, and tools used into a single unit of analysis. This makes it a suitable candidate for developing an understanding of how representations act as intermediaries in the dynamically evolving and collaborative processes of design.

Hutchins' framework can be developed further, returning it even closer to its roots in cognitive science. Cognitive science allows system descriptions in terms of the functional attributes of a cognitive processor. By disregarding the specifics of implementation, and looking to the higher level terms of what the system *does* rather than *is* (i.e. a functional description), the most basic constituents of a cognitive system can be said to consist of a sensory system, a system memory, a processor and a means of acting on that processed information if necessary. The are displayed diagramatically in fig. 3.1:

fig. 3.1. Functional description of a cognitive system.




- The *sensory mechanism* takes its inputs (in the form of representations or observed actions) from outside the cognitive system and passes it to the information processing unit in the form of representation.

- The *action generator* allows the production of outputs from the cognitive system in the form of actions or representations. It may also provide feedback to the information processor about the performance of the actions executed.

- '*Memory*' involves the creation of a representational state that is stored to organise subsequent activities; it receives representations from the information processor, and when required, passes them back to it. This storage function may be systematic, or serendipitous, arising through features in the world that are interpreted to inform the system of its past, current and possible future states.

- The *information processor* receives representations from the sensory system and acts upon them, to transform them, combine them or even destroy them. These representations may be stored in the system 'memory', acted upon to create outputs, or used to prime the sensory system to attend to particular inputs.

The implementation of a distributed cognitive system in a real world example can be highly complex: the four units of the functional cognitive system may not fit neatly into individual units - agents can perform several, if not all of the four functions of the system. For example, an engineer may be involved in performing calculations (information processing), they may act as a repository of knowledge (system memory), they may take incoming specifications as inputs to the system (as a sensory mechanism), and they may generate drawings as outputs (action generation).

Nevertheless, the functional description provided within this framework allows the analysis of problem solving with any size of cognitive unit, because the individual is no longer the central focus of enquiry, although they may make up components of the system. It is useful to describe the activity of the cognitive unit using these four components because this framework allows the analyst to understand the functions of the representational states and the activities observed. This demonstrates *what* the components of the system are involved in, and *how* they relate to others in information processing activity.

### 3.4.4 The unit of analysis

The unit of analysis for a distributed cognitive system incorporates a number of features, including possibly multiple agents and artefacts, with an organisational system determining how these interact with one another. Within a distributed cognitive system, actors and artefacts are considered to be equally important in problem solving, and these make up the *functional system*[4] (Hutchins, 1995a) of activity. The functional system takes in inputs (representations) and processes these representations by propagating them around the units of the cognitive system. Thus the aim of DC is to understand how intelligence is manifested *at the systems level* and not the individual cognitive level (Hutchins, ibid.).

Systems may be interacting, interrelated, or have independent components that combine to perform specific purposes. For example, a car is a system of parts whose purpose is to transport people on roads. It is impossible to understand a system by analysing its individual parts; only through examining the relationships between the components parts is it possible to understand the system. Thus, for a car, an inventory would show that the car was intact even if the spark plugs were in the back seat; to understand why it failed to start, the relationship of spark plugs to engine is important. However, at another level, this understanding of a car is useless, for example when trying to analyse the properties of a road transport system: the grain of analysis is all critical. The emergent properties arising through relationships between the elements of the unit of analysis (in this case, the car) is central to the understanding of DC - 'the distributed system of cognitions is more than the sum of its components; thus, its operations cannot be understood by examination of its isolated parts, and the system should be examined as a whole' (Salomon, 1993,

[4] The terms functional system (Hutchins, 1995a), functional unit (Rogers & Ellis, 1994) and complex cognitive system (Flor and Hutchins, 1992) have all been used to describe the system under examination, and are interchangeable. This unit of analysis appears to derive from activity theory (Luria, 1979). The functional system is akin to the 'boundaries' of a cybernetic system (Rzevski, 1981).

p120). The emergent properties of the system arise out of the interactions of parts to generate a new phenomenon larger than the activities of those parts.

The functional system has emergent properties that cannot be specified by adhering to an individualistic perspective: 'the unit of analysis is flexible and allows an entire system of actors and artifacts to be considered an intelligent gestalt with properties both similar and radically different from the cognitive properties of individual actors' (Flor, 1997). The system has different properties to the individuals participating in the activity or system; it, and not the individuals, performs the task and the functional system must therefore be treated (at least functionally) as an intelligent entity.

The goal of analysis is to describe how 'the distributed structures, which make up the functional system, are coordinated by analysing the various contributions of the environment in which the work activity takes place, the representational media [....], the interactions of individuals with each other and their interactional use of artefacts' (Rogers, 1993, p. 297). Here, DC and situated action have much in common, because they both consider behaviour to be co-ordinated, at least in part, through an environment rich in organising resources. DC provides a framework to both conceptualise and analyse complex and socially distributed work activities involving technological artefacts and other tools. It operates by focusing on the interactions and actions that are central to co-ordinating distributed work activities (Rogers, 1993).

### 3.4.5 The role of representations

Within this thesis, the word 'representation' is used to describe the way in which a system stores knowledge about a domain[5]. It is a symbolic notion, denoting the thing represent*ed* (Norman, 1991). Representations may be encoded internally in the individual (i.e. mentally), or in the environment (in an artefact). They may encode knowledge about things, or about the organisation of things. They can encode the same knowledge in different ways that are functionally and logically equivalent (problem isomorphs), yet can be manipulated by individuals or systems in different ways.

The importance of the representation in distributed cognition comes from the information processing metaphor of cognitive science, where information is acted upon and transformed computationally (Newell and Simon, 1972). Mental cognition is assumed to be an instance of a Turing Machine, operating through computational mechanisms (Pylyshyn, 1984). Within this computational view of cognitive science,

[5] The word 'representation' has a confusing meaning: it can also be used in social science to mean the way that fieldwork is documented and used to 'represent' the narrative.

changes to the form of the representations are a part of problem solving, because changing the representation of a problem changes the problem itself. Successive transformations on a representation can transform the initial state into the desired state (Simon, 1981). The computational transformation of a problem state (a representation of the problem) through a 'problem space' (composed of the start state, goal state, resources and constraints) into a goal state occurs through the propagation of that representation across various representational structures (Simon, 1981; Kahney, 1993; Hutchins and Klausen, 1991; Hutchins, 1995a,b). In humans, these representational structures would be neural pathways. In DC, cognition takes the form of a computation on a problem representation, involving 'the propagation of representational state across a variety of [representational] media' (Hutchins, 1995a, p. xvi; also Hutchins and Klausen, 1991; Hutchins, 1995b), the difference to individual cognition being that the media hypothesised are not limited to internal, mentally held representational states.

Different forms of representational media have particular properties that constrain the uses to which their representations can be put and how they can be accessed. Changes in the medium of this represented information may alter the cognitive state of the system (Hutchins and Klausen, 1991). The forms of representation used, the organisation of the representations and their media, and the interactions of the actors are therefore critical to the task operations performed by the functional system. Hutchins (1995a) provides an example of computational activities and representational transformations in the 'fix cycle' of a navigational system, where the navigational system captures knowledge in the world as representations, and successively re-represents them until they can be applied to a chart to represent a physical location (the system goal). The representational states are propagated across a complex set of media, and the goal of spatial orientation is achieved through bringing the representational states of these media into *co-ordination*[6] with one another. Through bringing representations in the system into co-ordination with each other, a representation can be propagated through the distributed cognitive system, being continually modified and processed by a number of individuals and artefacts, until the desired result is reached. Navigation is therefore an emergent property arising out of the combined efforts of collaborating individuals, none of whom can be said to individually determine the course of the process.

Cognitive science has traditionally studied the transmission of representations through the cognitive system using the computational metaphor of information

[6] Bringing the representations into co-ordination with one other involves a process of mapping a representation from one media onto another.

processing theory. Through expanding cognition across a unit greater than the individual, to computational accounts of group cognition, the identification of representational states used by a system can allow researchers to examine the information processing capabilities of the larger cognitive unit. This computational approach is applicable to all areas of collaborative human activity, and will be applied to describe the area of engineering design in later chapters.

## 3.5 Research methodology

### 3.5.1 Methodological issues

The analytic framework developed earlier in the chapter provides a basis for understanding how collaborative engineering design work is co-ordinated and through which design work is performed. DC allows the identification of important features operating in collaboration. It also demonstrates how representations are used in information processing activities by the designers in the performance of their work. However, to make claims about how collaboration is maintained and then to fill out the framework with the representations and processes of design work, data will have to be collected about designers involved in real world collaborative design.

As a framework for describing and explaining group cognition, distributed cognition is not a method - its practitioners are therefore able to be eclectic in the range of approaches that they can use. Most of the studies in the literature are observational, although they have been applied in various ways. The analyst is therefore free to select the method of data collection that is most appropriate to the functional system under examination. One such method, ethnography, is applied as the means of data collection in this thesis. However, the ethnographic method was developed independently of the distributed cognitive framework and must be adapted to fulfil its requirements as a tool for data collection. The following sections outline the method used and develop it with respect to the problem domain. It examines the reasons behind the selection of the method, and highlights and discusses issues arising from its use. This is developed in the context of cognitive science and its requirements for the collection of data that is explanitorially adequate.

### 3.5.2 Research methodologies and cognitive science

The psychological sciences have appropriated the experimental method to examine behaviour, a feature of psychology known by qualitative researchers as 'physics envy'. Psychology generally uses experiments to answer its questions, but it nevertheless does not argue that reliable knowledge can *only* be obtained through experimentation (Bower and Clapper, 1989). Science methodologies themselves are not solely experimental: astronomy, possibly the parent of scientific method itself, has had to content itself with an observational method (ibid.).

Whilst mainstream cognitive theories have generally taken an experimental approach, in everyday activity, cognition is situated within a social and physical context, and it rarely, if ever occurs in a situation where context does not play a part in it (Cole, 1977; Butterworth, 1992). This accounts for many of the problems faced in designing psychological experiments, where the high number of possible variables must be controlled, and where the environmental conditions cannot be allowed to play a part in the result. However, where cognition occurs *through* the interactions of people and their contexts (Suchman, 1987; Lave, 1988; Norman, 1993; Hutchins, 1995a), as described through the framework of distributed cognition, it is the real world conditions themselves that are the point of departure for the enquiry, and as such, an experimental approach is not applicable.

One approach to examining real world settings in social science is naturalistic research, the approach adopted in this thesis. Naturalistic research allows us to 'describe what happens in the setting, how the people involved see their own actions and those of others, and the contexts in which the action takes place' (Hammersley and Atkinson, 1995, p. 6). Indeed, there has been a long history of naturalistic observation in social psychology, because it is good at providing descriptive generalisations about classes of phenomena (Bower and Clapper, 1989).

A cognitive framework is developed below that can be applied to form a basis around which the naturalistic data collected will be analysed. This description begins by describing activities in the terms of cognitive science, framing this in terms of the representations that make up the process. In turn, this guides the methods of data collection, specifying the material required to satisfy the needs of an adequate explanation of the observed behaviours at a cognitive level.

### 3.5.3 Developing a research methodology for distributed cognition

DC studies the way that work is socially distributed across the functional system, and situated in the context of a physical environment. However, unlike traditional cognitive science, the scientific rigour of the experimental approach (e.g. Schönpflug, 1988) is not possible, nor indeed is it appropriate for the study of collaborative design within the distributed cognitive framework. Appropriate methods of examining the cognitive characteristics of the unit of enquiry must be used, in this case, the unit of enquiry being the functional system. The method of data collection used must be sensitive to the context of activity, so that the interactions within the functional system are accessible to the analyst. However, to demonstrate it relevance, such an approach must clearly define its terms, methods, boundaries and limitations.

The method chosen in this thesis draws from the qualitative methods of social science, yet retains the analytic framework supplied by psychology and cognitive science. This means that the research retains the strength drawn from its cognitive roots, but can go beyond the limitations of mainstream experimental methodologies in cognitive research. This is a new form of research that does not conform to the norms of either psychology or sociology and anthropology. However, the eclectic nature of the approach is not wholly novel; it adapts the naturalistic traditions and methods of data collection, and applies this to a cognitive method of analysis. Only if both of these features can be mutually satisfied can the approach be considered as methodologically sound.

### 3.5.4 Levels of description in information processing activity

Marr (1982) describes three levels at which information processing systems need to be described to account for a satisfactory explanation of the task. Marr applied these three levels to understanding the underlying cognitive and computational basis of vision, although they can also be applied to distributed cognitive systems (Hutchins, 1995a), such as navigation teams or engineering organisations. The three levels guide the selection of a means of data collection by specifying what is required to satisfy the needs of an adequate explanation of the observed behaviours at a cognitive level. The three levels of description are described in the table below:

Table no 3.1. Marr's three levels of information processing activity.

| **Features** | **Computational level** | **Representational level** | **Implementational level** |
|---|---|---|---|
| *Function* | Determines goal of the computation. | Determines how inputs are transformed into outputs. | Determines how computational machinery is embodied in a setting. |
| *Form of description* | Makes explicit the entities operated on. | Specifies media and representations available to operate on. | Fieldwork: cognitive description of the system. |
| *Results of description* | Specifies high level constraints on activity. | Description of the representations available to achieve computation. | Organisation of components and mechanisms used in transforming representations. |

A theory of collaborative engineering design must specify the three areas clearly to achieve a full description of why, on what, and how the cognitive processes operate within the system. By making each layer explicit, the theory becomes open to objective analysis and the possibility of empirical examination (Marr, 1982).

### 3.5.5 Data collection and distributed cognition

The functional system is the unit of analysis for DC, forming a collection of individuals, artefacts and their relations to each other in a task. Analysis therefore begins by specifying the units involved in the functional system (the representational level), and then by positing a system goal (Nardi, 1992) for the functional system (the computational level of description). Once these have been determined, the means by which this goal is achieved is examined (the implementational level). This will result in a description of the pathways that information flows through, and the external structures that are created and used prior to the solution of that goal, (said to be the equivalent of examining the systems' 'mental state' - Flor and Hutchins, 1992). Information and knowledge can be held as (individual) mental, social and external (including technological) states and may be transformed between the members of the functional system. The work involved in data collection is observational: DC researchers look for information-representation transitions (Flor and Hutchins, 1992) that result in the co-ordination of activity and computations. These occur through the media of knowledge representation.

Knowledge is propagated around the functional unit through a number of communicative pathways (Rogers and Ellis, 1994): verbal; non-verbal; inter-modal transformations (e.g. verbal to text); and by construction of new representations by mental computation in combination with external representations (e.g. operations on tools). All of these can be observed directly. The organisation of this knowledge is important in determining its use, because it constitutes the system's expertise. This knowledge is distributed across the heads of actors *and* in the organisation of tools and the work environment (Hutchins and Klausen, 1991). Data collection must involve descriptions of how the organisation of this distributed knowledge is used in the performance of the functional systems' goals.

There are four areas that require analysis to get a full picture of the knowledge transitions within the system under examination (Rogers and Ellis, 1994):

- by the way that the work environment structures work practice,
- by changes within the representational media,
- by the interactions of the individuals with each other,
- by the interactions of the individuals with system artefacts.

The form of this analysis involves detailed studies of the workplace to analyse the role of technology and work practice in system behaviour. The method by which this is achieved is through performing a *cognitive ethnography* (Hutchins, 1995a), that is, through fieldwork that places emphasis on the representational and representation transforming characteristics of the functional system under observation.

## 3.6 An introduction to workplace studies

### 3.6.1 Workplace studies and distributed cognition

The methodological framework for data collection within the analytic framework of DC must identify the representations and processes operating within the functional system. From the data collection, these representations and processes can be brought together in the analysis to describe how they are combined and mediate the collaborative component of work. The requirements of the analytic framework are therefore important in the selection of a method for data collection, because they determine what data is relevant and needs to be collected from the workplace to develop an adequate explanation for the phenomena observed. A work activity that involves actors performing within a complex, real world setting requires a method of examination allowing the study of those actors within that setting. The methods chosen for data collection under these circumstances are therefore bounded with the requirement that an observational study of design work be performed, because removing actors from the context of their activity will change their relationships to the task, to their social interactions with one another, and to their use of tools and technology (the rationale for naturalistic research).

The method of research used in the examination of design, as already stated earlier, will differ from the experimental approach to data collection because of its reliance on controlling the subject and the setting to a limited number of variables: behaviour in the laboratory is not always the same as behaviour in the world. The experimental approach is also limited in that it seeks to answer a hypothesis. This research does not seek to answer a specific hypothesis, or one that was predetermined prior to the research study. Its remit is to examine how work is performed by collaborating actors with a much broader focus of study. Methods of qualitative research are far more suited to the collection of this kind of data.

To understand the differences between quantitative approaches to research and qualitative techniques, their methods are compared below:

**quantitative research** - associated with the experimental method, where there is a high degree of confidence in the data collected.

**qualitative research** - research is focused on the context and integrity of the material. The account is not built directly or only from the data collected. Interpretation and subjectivity are central features of the described account of the phenomena, because the research forms part of a debate and is not a 'fixed truth' (Banister *et al*, 1994).

Data collection in the field (fieldwork) or workplace (hence, workplace studies) requires a principled approach to provide useful and substantiated information on activity in the domain of interest. Material must be presented in a way that adequately describes the situation, and in a way that the reader can make their own conclusions about the quality of the analytic inferences made from this material. This will entail bringing something from the setting to the analysis, and this traditionally involves descriptions of observed activities and directly quoted discourse. However, to an extent, the qualitative researcher must be 'taken on trust' to provide a truthful description of activity in the workplace. One qualitative research method in particular has the qualities demanded of a research method for the collection of data that meshes with the demands made by distributed cognition: the ethnographic method.

### 3.6.2 Ethnography - 'making work visible'

Ethnographic analysis attempts to show *how* work is organised (Hughes, Randall and Shapiro, 1992). It has been used to examine the social organisation of groups and has become a central method of analysing workplace activity in CSCW (Hughes, Randall and Shapiro 1992; Grudin and Grinter, 1995; Rogers, 1992, 1994; Heath and Luff, 1991). Woolgar (1988) describes it as: '...a style of research in which the observer adopts the stance of an anthropologist coming upon the phenomenon for the first time. One takes the perspective of a stranger as a way of highlighting the taken-for-granted practices of the natives under study.' Van Maanen (1979) describes it as being used to 'uncover and explicate the ways in which people in particular work settings come to understand, account for, take action and otherwise manage their day-to-day situation' (p. 540). The method is particularly useful in capturing descriptions of socio-historical and environmentally situated behaviours because of its methodologically unstructured nature, which allows a large degree of adaptability in the field. Ethnography also does not limit itself to the examination of predetermined phenomena, which is important for domains where the phenomena are not yet fully understood.

Many ethnographies take place over a period of many years, in which the fieldworker immerses themselves in the domain of study. However, not all fieldwork needs to be extended over such a long timespan, and this is the case particularly where the study takes place in a domain where the language, patterns of social interaction and other features of work are not totally alien to the ethnographer. In the case of a study of a subculture (rather than a true culture) as is the case with designers, the cultural norms differ only in partial degree to those normally experienced by the fieldworker (Bucciarelli, 1994), who more usually operates in a totally different culture, often using a foreign language. This is reflected in CSCW, where there has been a movement towards 'quick and dirty ethnography' and where the fieldwork is of a briefer duration than this extended period of immersion (Hughes, King, Rodden and Andersen, 1994). Because of this decreased level of immersion in the field, the research described in this thesis takes an approach based on the principles of ethnography, whilst hesitating to go so far as to call itself a true ethnography - it involves 'ethnographically informed fieldwork'.

The ethnographic approach allows the examination of features of work that are not apparent from a more cursory observational examination of work practice. Although people may describe the work that they do in clear terms, they do not necessarily perform it in that way (Suchman, 1987; Woolgar, 1994). These are normative (Hutchins, 1995a), or canonical (Brown and Duguid, 1991) descriptions of work: observed reality is not necessarily the same as that described by its participants. This may occur for a number of reasons, although it is likely that much of this knowledge is not explicitly recognised by its users (Rzevski, 1984) - it is therefore *tacit* (Goguen, 1994). Tacit knowledge is inaccessible, and cannot be articulated by those who use it.

Many of the normative rules within organisations exist in documents describing 'organisational procedures'. However, it appears that these are used as resources for action (Suchman, 1987, 1990), and not as absolute rules that determine behaviour. These 'rules' are therefore an ideal of the work process, but should not be confused with the work as enacted. Descriptions of work processes for CSCW design need to make this distinction clear, because there are two ways to describe work: as the way things are supposed to work and the way that they do work (Grudin, 1994). In practice, normative descriptions of work may be abstract, not detailing the exact mechanisms of action, and leaving these to be locally determined by the situational requirements and the resources at hand. The process of fieldwork attempts to prise apart such normative descriptions of work and practice, as performed by actors in situ. The fieldworker must therefore attempt to understand the activity observed in terms of the way that such activity is understood and practised by its participants rather than through simple descriptions of that work.

An understanding of work cannot be gained from a single individual, because they will not be able to describe all of the processes that go on in design because of the distributed nature of that activity. Participants to an activity may not be aware of parts of the work system that do not intrude on their own work areas, so that the task as a whole cannot be viewed from a single perspective, only from a more global perspective, taking in components from the whole activity system. Through an observation of the work, and the communication that links agents involved in that work, a more realistic picture of the design process can be built up that does not rely on the perspective of a single person or their subjective opinions of work.

### 3.6.3 The ecological basis of the ethnographic method

Ethnographers propose that 'things' (the object of examination) should be studied in their natural state (naturalism) - and this precludes the experimental method. Because behaviour cannot be divorced from the situation, an 'in situ' study of behaviour must be conducted to understand the unit under analysis (Winograd and Flores, 1986; Bannon and Bødker, 1991; Hutchins, 1995a). The primary aim is therefore to describe the setting (or ecology), context, and both the actions performed, and the way that participants interpret their own actions. This epistemological gulf between ethnographic and psychological approaches to the study of cognition and work has resulted in a long running intellectual debate between psychologists and ethnographers (see Monk *et al.*, 1993). When choosing to use ethnography as a technique, the needs of relevance must be balanced against those of trust in their applicability (the qualitative - quantitative debate). This will involve matching the needs of ecological validity (high for ethnography) and reliability (i.e. can the results be reproduced - low for ethnography, but high for experimental approaches) to the domain of enquiry and the nature of the research problem.

Ethnography is characterised by -

- data[7] gathered from a range of sources (data triangulation)
- an in depth study of one or more situations (source triangulation)
- the study of data in context - good at revealing complexity, rather than stripping it away
- an unstructured approach to data gathering, allowing key issues to emerge through ongoing analysis; it does not involve hypothesis testing.

In a naturalistically observed complex environment, such as a workplace, people draw information from a huge number of sources that cannot be replicated in an experimental or laboratory based environment. In particular, observations emanating from experimental studies ignore situational and organisational features (Anderson and Sharrock, 1993; Norman 1993). The ethnographic approach is therefore the most appropriate means of analysing the cognitive activities performed by the functional system of design, and will be used in gathering material for a DC analysis of design. A 'cognitive ethnography' can provide a method for discovering the representations (and mechanisms for their propagation) which are operative within particular activity systems (Hazelhurst, 1996). Using distributed cognition as an analytic framework, the ethnographically informed fieldwork can be used to gather material which can then

[7] The use of the word 'data' is problematic because it implies that there are hard facts within it; rather ethnography is a form of 'reportage' (Anderson, 1994). However, data is the term used in Agar (1980) and Van Maanen (1979), and the term will be used bearing this criticism in mind.

be examined and documented, picking out the salient points relating to the computational, or cognitive, characteristics of the functional unit.

### 3.6.4 Analysis of the cognitive ethnographic data

Analysis of the ethnographic data will be multidisciplinary, drawing from cognitive theory, and borrowing from the intellectual heritage of anthropology and sociology. This perspective will influence data collection, placing emphasis on the role of artefacts, and collaboration around these artefacts. Observations will therefore centre around the types of artefacts that are used or created, how they are used, who they are used by, how changes are made to them, and how the organisation structures access to these artefacts.

In a cognitive description of a functional system for engineering design, Marr's description at the level of 'implementation' will involve the main cognitive ethnographic component of the work. This involves descriptions of the design group structure, and how the representations described above are transformed to perform the computational functions of engineering design. The cognitive ethnography will involve moving from first order concepts (the observed data), towards second order concepts (theories about the data) that account for patterns in the first order data (Van Maanen, 1979). The distributed cognitive analysis will be the method used to transform the observed data from the fieldwork into a theory of the patterning observed. The process is iterative, involving data collection, the creation of a 'working theory', followed by repeated sequences of observations and theory matching exercises. The result of this is an account[8] of the distributed cognitive processes that underpin the activity of the observed functional system.

A cognitive system is necessary to carry out intelligent actions, consisting of a control mechanism, a memory and a set of operations to act on an input, and to generate an output. The task of the DC theorist is therefore to examine the data and to identify the set of processes that create, modify, reproduce, or transform representational structures in that system. The goal of the researcher in cognitive ethnography is to provide an account of how the distributed structures of the functional system are co-ordinated (Rogers and Ellis, 1994).

[8] Although not *the* account (Agar, 1980). Ethnographic reportage is a subjective means of describing a situation, and there can be no single 'correct' description - however, some descriptions of work may be more appropriate under certain conditions.

## 3.7 Conclusion

The chapter examines how cognitive science can be used as a means of examining units of activity greater than that of the individual to include several people, tools and the structure of the environment in problem solving behaviour. It outlines and develops the theoretical basis behind distributed cognition and demonstrates how it can be used to guide data collection and analyse settings. The role of representations and processes is examined, and their relevance and importance to the performance and understanding of collaborative activities is highlighted. A method of data collection, ethnographically informed fieldwork, is also outlined that can be used to collect material for the analysis.

In principle, the framework of distributed cognition is applicable to the examination of all areas of multiparticipant activity. One such area is that of engineering design, a particular instance of collaborative activity. Studies of work, such as those revealed in the fieldwork and analysed within a theoretical framework can be used to reveal the social organisation of activities, the use of artefacts, and the mechanisms co-ordinating the behaviours of collaborating individuals. The following chapters will attempt to reveal these patterns in a study of collaboration in engineering design.

# Chapter 4

# Applying Distributed Cognition to Design

## 4.1 Overview

The chapter describes how the framework of distributed cognition outlined in chapter three will be applied to the work of engineering design. It clarifies the nature of work in the construction industry, so that appropriate material is collected in the fieldwork for analysis. Through making explicit the resources used by engineering designers, information systems developers can make better informed decisions about the technology that supports the work performed in the design systems examined. The analyst must therefore determine what the subject of examination is, and how the data collection and analysis will be performed, to provide both valid and relevant information about the domain of interest.

The research documented in the thesis does not attempt to approach the domain from the traditional engineering or information systems approaches, because they do not incorporate the understandings that social science can bring to problems. Social science does not attempt to answer design problems, but seeks to discover the underlying nature of the problem. This research is intended to supplement existing work on design rather then neatly fitting into these approaches. As such, it is not wedded to a particular development framework. The focus is therefore on understanding design activity, and not in directly specifying technology for design.

Distributed cognition focuses on the processes and representations used in the co-ordination and performance of work. It allows the analyst to examine how information processing occurs through the propagation of a representation across media with different properties, transforming the representation of the problem into a representation of the solution. In applying the cognitive science paradigm to design, the representation of the design states in the design system must be considered as to how they interact with the other representations in the system. An examination and description of the processes, representations and other design system details is required to provide answers that will allow a cognitive level of analysis.

Whilst Hutchins (1995a,b) and others (Rogers, 1993; Halverson, 1994; Hazelhurst, 1994) provide examples of how individual examples of analysis are performed, these are specific to particular domains. The approach taken in this thesis draws from these studies by adopting and adapting the approach within a novel setting to demonstrate how design is socially organised. Such an analysis can demonstrate how the social, organisational and technical properties of the design system interact to support collaborative design. The work of design in construction has several features that distinguish it from the areas previously examined using distributed cognition, and it therefore requires a customised approach applicable to the domain. These differences, and the challenges that they impose on the use of DC in construction are explored and considered in the following sections.

## 4.2 Design in context

The literature on *design* in the area of computer supported co-operative work can be misleading because it is used to describe two unrelated areas. One meaning refers to 'systems design' (called systems development in the thesis to avoid confusion), in which CSCW (more precisely, computer supported co-operative design) hopes to inform the people who develop technological systems so that they can build systems that are sensitive to the social, organisational and cognitive aspects of the workplace. CSCD researchers therefore hope to provide recommendations in a form that systems designers can apply to developing computer or technological systems that are appropriate for the conditions that users face. The other meaning of 'design' is that which the users of such technology themselves perform (described in section 2.2), including design domains such as architecture, engineering, craft work, or even systems development itself. Each is considered in turn.

The aim of this thesis is to apply a better understanding of situated and collaborative engineering design to the development of technology, an applied motivation that falls into the area of cognitive engineering (Norman, 1986a; Woods and Roth, 1988; Anderson, 1996). Cognitive engineering relates to the study of human behaviour in complex worlds, and of the architecture of multiple agents (Woods and Roth, 1988) with the aim of system redesign in mind. System redesign relates to all aspects of systems behaviour; in the domain of HCI it is usually applied to the development of computer systems. However, redesign of many areas of the system may be possible: in CSCW, technological change is interrelated with organisational change because each appears to change the patterns of activity of the other. Any redesign of systems through the implementation of computer technology will therefore need to have some understanding of the change that it may generate. Technical solutions that are implemented when system developers fail to understand how people work, communicate and co-ordinate their activities or without an appropriate understanding of the nature of work are apt to go awry (Grudin, 1988).

Cognitive engineering seeks to understand the interactions of people, computers and organisations, and improve these interactions (Anderson, 1996). This involves investigation of the cognitive and social constraints on the use of existing technological devices and to incorporate these constraints into the design of new devices (ibid.). Distributed cognition falls neatly into cognitive engineering because of its explicit rationale of investigating just these constraints.

Distributed cognition is *not* a means of deriving a design from its resultant findings. This is not its intention. The development of technology is a creative process that arises through the interaction of a number of contingent environmental concerns. There are various pressures on the design process, including what the client organisation is prepared to accept as a technological solution, the time and price constraints on development, the existing technologies available for development, the number of, and skills of the developers, all of which will determine the types of technology that can be developed.

In this thesis, DC is used to examine the mechanisms involved in co-ordinating collaborative work. This form of analysis can provide support for systems developers by giving them a resource with the potential to help them understand the work involved in engineering design, allowing them to make the creative leap that is the impetus for the generation of technology. It is possible to use the analysis to make general suggestions for design, but these should be regarded more as a set of informed guesses than a completed requirements specification for the settings examined. The key to understanding the distributed cognitive analysis of the data is that it is a means of making explicit the nature of the activity, one that is dependant on the interactions of multiple participants, a wide range of tools and other organising resources. The development of appropriate technologies for complex settings can only take place if the setting is itself understood; technologies that account for the particularities of these settings are more likely to be successfully and effectively incorporated into work practice.

## 4.3 The organisation of design in construction

### 4.3.1 Navigation and construction

To develop a means of examining the construction process, previous studies using the framework of distributed cognition will be used to guide the fieldwork and its subsequent analysis. However, these previous studies have taken place in very different settings to that of engineering design, and this thesis must therefore differ in its approach to the problem.

The previously best documented study of distributed cognition has been applied to navigational systems (Hutchins, 1995a), and involving a closed system of highly formalised and learned behaviour. Engineering design and the navigation of ocean-going vessels have a number of similarities: they both involve several people who must collaborate to achieve a satisfactory outcome; they both involve explicit processes, such as archiving, communication and quality control, which must be followed in performing work; and they both utilise tools in performing their duties and in communicating their representational states to other individuals in the functional system. However, engineering systems also have several very different characteristics to those of navigational systems. To demonstrate where the methods and approach used in the study of navigation cannot be directly applied to describe cognitive behaviour in engineering, the two are compared below.

Whilst there are obvious differences between any two such systems, a number of important factors are noted here for the purpose of comparison (see table 4.1):

Table 4.1. A comparison of navigation and engineering design.

| **Areas** | **Navigation** | **Design** |
|---|---|---|
| *Access to resources* | Closed system | Open system |
| *Problem structure* | Well-structured. | Ill-structured |
| *Organisational structure* | Pre-specified modes of operation. | Organisation only partly pre-determined |
| *Cycle duration* | Relatively short. | Process can take many years. |
| *Problem dynamics* | Unchanging process. | Relatively short project duration |

*Access to resources*

The main difference between navigation and design can be described in terms of the distinction between an open and a closed system. In navigation, the system is closed: no external agents are permitted to involve themselves in the system, and the process has a fixed and restricted set of resources. In construction, the system is open: its participants can call on a larger set of resources not initially specified, and there is more scope for creative interpretation with the use of resources available.

*Problem structure*

The problems that the two systems have to solve are structured in different ways. In navigation, the problem is 'well-structured' prior to its solution; the task is repetitive and actors are well practised in performing the task. In construction, the problem is 'ill-structured' and only becomes well-structured through collaboration: the designers learn about the problem during problem solving, because many of the techniques they use are specific to the problem in hand.

*Organisational structure*

The methods that are used to organise the co-ordination of activity differ between navigational practice and in construction design. In navigation, the communication pathways are well specified and constrained to pre-specified modes of operation. These are enforced by naval regulations, which proscribe the division of labour on particular tasks. However, in construction, these communication pathways are not well specified prior to problem solving, and the organisation of functional units is only partially constrained by pre-determined modes of operation. There are no absolute organisational structures, and the artefacts, communication pathways and participants available may change over time. Some processes are formally specified, but many are generated in an *ad hoc* fashion. In addition, the constraints on the design process may change as legislation and professional standards are altered.

*Cycle duration*

The duration of the activity cycle differs substantially between the two areas. In navigation, the 'fix cycle' is of short duration (a matter of minutes or seconds). These fix cycles are 'snapshots' in time, and each involves taking a bearing of their present location. However, in construction, the design process can take many years. During this time, new behaviours and processes may develop as problems arise, so there may be no effective precedents to behaviour.

*Problem dynamics*

The changing nature of the problems faced by the navigators and by the construction designers differs substantially: this has implications for the way that strategies for problem solving develop and enter the culture of the workplace. Navigation by triangulation is an unchanging process, developed over centuries of practice[1]. The standard operating procedure can remain unchanged over multiple fix cycles, and though each may be of short duration in themselves, they are highly repetitive, although there are a small number of choices that can be made, the selection of which

[1] The navigation processes described by Hutchins may have changed with the introduction of the Global Positioning System (GPS) through change to the problem of positional location itself. This is because the problem of location has changed: satellite information rather than visual information is required for location. The GPS system has the potential to reduce the training required and number of agents within the system. The configuration of the functional navigational system will therefore be unlikely to remain unchanged.

is dependant on constraints such as the time and personnel available. In construction, the duration of project determines the organisation of the functional system; over time procedures evolve, adapt and develop. Most procedures are defined at an abstract level, and can be changed as circumstances demand. The relatively short duration of projects (usually less than five years) is determining factor on system organisation: there is little time for new procedures to evolve, adapt and develop to the point where they can be directly applied. Many procedures are defined at an abstract level, and left to the interpretation of individuals to decide on what actions to take, although prior experience may prepare agents for particular types of situation.

However, possibly the most significant difference between navigation and building design is that the work itself is different, with very different goals, technical resources and contexts of use. Nevertheless, these differences do not mean that engineering and navigation are impossible to reconcile: they are both information processing systems with a similar high level structure. Cognitive theory within psychology is used to examine the work of individuals on specific tasks, and the distributed approach (which focuses on the analysis of informational structure) extends this to examine collaborative tasks. Because of the ways that navigation and design differ from each other, the methods used to examine them will also have to differ. In addition, the findings that relate to the two domains are also likely to diverge.

### 4.3.2 The engineering process

The work involved in construction and engineering encompasses an enormous range of activities and processes that go far beyond the remit of this thesis. The fieldwork attempts to distil the most salient elements of the work, giving the degree of the background information necessary to understand the co-ordination of work and the role of the situation in organising activity. The work documented in this thesis is not intended to be a complete description of the domain, and as such, should not be judged on the completeness of the material, but on its application to the problem at hand. This will involve understanding how design is performed within a context, and using this understanding to help develop technology to support such activities.

The engineering process is one that involves a huge range of people, tools and materials. There are many ways to fabricate structures, and many different forms that such constructions can take. The role of the engineering designers is to chart a path through this range of methods and to erect their designs as cheaply as possible, within its constraints; outside of these restrictions, the designers are free to determine how best to proceed themselves.

Engineering is a relatively homogenous discipline; educational courses for engineers of whatever field are highly similar, and engineers are trained to understand a common language, encapsulated in mathematical terms, and in the graphical language of 'the drawing' (Henderson, 1995). However, it is not just the engineers that can have an impact on the engineering process - they are a part of engineering design (albeit a central focus), but not the only part. Other stakeholder groups can have an impact on how an engineering project develops, from the client reviewing the designs and requiring changes, to workers interpreting information from the drawings on the construction site. Even the tools that are available determine a part of the design process, by limiting or enhancing the options available to the participants. This study therefore includes all of the entities involved in design and is process centred, rather than person centred, although people are considered when involved in a process.

### 4.3.3 Participants in the design process

Following the approach set out by distributed cognition, the agents involved in the information processing activity are described where relevant to the design process. These participants are examined in terms of their roles, the skills that they bring to the work, and the tasks they are involved in. The three following groups were identified as centrally involved in the design process. Other groups form a component of the process, but are peripheral enough to describe as the need to do so arises.

#### Architects

Architects are concept developers who design the initial physical structure of the construction through interpreting the basic specifications of the client (functions that the structure must have) as a physical form. They are not directly concerned with the implementation of the design. Architects pass their designs to the engineers who may require them to make modifications to the designed structures so that they can be constructed more cheaply or so that they conform to the physical limitations of the available materials. Whilst a study of architects would have been useful, this was not possible; architects were however observed indirectly in the study of a consultant engineering organisation, documented in Appendix B.

#### Engineers

Engineers are the workhorses of the design process; they are the people responsible for the construction process itself, involving the transformation of the architectural design into a constructable form. There are many types of engineer, each specialised in a different domain, such as civil, structural, mechanical, electrical and acoustic engineering. Engineers may operate across a number of commercial organisations, which may be responsible for different areas of the design. In this study, engineers operated in two capacities - in transforming architectural specifications into constructable designs, known as engineering designs (consulting engineers), and in transforming engineering designs into constructions (civil engineers). Engineers are also involved in co-ordination activities with other parties to the construction process, including groups as diverse as construction workers, sub-contractors, managers, quantity surveyors, suppliers and architects.

**Construction workers**

Construction workers are involved in the process of building the structures specified by the engineers. They are generally managed by skilled supervisors (foremen and gangers), who themselves work under the direction of engineers. Construction workers apply the instructions that they are given as actions, such as erecting scaffolding, building concrete moulds and operating machinery. As a group, they communicate solely with the engineers with regard to the design work.

### 4.3.4 A novel perspective on engineering design

A great deal of research exists about engineering design (section 2.2). However, this existing research does not take account of the cognitive processes that arise through interaction and that organise the structure of the design problem. The research described in this thesis adds a *complementary* perspective to the existing base of knowledge on engineering design by examining this neglected area. It draws from the social sciences and is not intended to integrate cleanly with any existing theory, but to be used as a resource for better understanding of the domain. To demonstrate how engineering design operates within this brief, the thesis examines the collaboration between the agents involved, the range of tools used in the activity, and how it is situated within a complex and often highly dynamic environment. This process of discovery begins with a description of design in the terms of cognitive science, to generate 'a distributed cognition of engineering design', framed in terms of the representations that make up the design process.

Any account of engineering design must answer the question of how the abstract design problem faced by the problem holders can be transformed into a representation of a physical construction that solves the problem. Problem solving theory would idealise this as moving through a problem space, performing some form of means-ends analysis (Kahaney, 1993) until the goal state is achieved. However, the specifics of construction work intrude into this perspective of theoretical design, to set a number of physical constraints on the design process. This is the starting point of this investigation into engineering design, and it leads to several fundamental principles that underpin design activity in the world. The approach used in this thesis breaks free of the locked conceptual frames that restrict existing research into design (see section 2.2), by beginning with an examination of practice, and only then using this to build theories about action. This approach differs from the traditional cognitive approaches to the study of design, which begin with problem solving theory and impose this structure on subsequent studies of design (e.g. Simon, 1981; Goel & Pirolli, 1998, 1992). These traditional approaches pre-determine the nature of the problem faced by designers and have led to questionable assumptions about what that they ask of it (an ontological concern).

At a very general level, it is possible to specify what design involves, without determining the specifics of how it is performed. To carry out design, those involved must decide on how to achieve a given goal state, or solution; they must be able to see their current state at a given time and compare it to their goal state, and they must be able to adapt their behaviour to these changing circumstances. This corresponds to the functional cognitive system (section 3.4.4), where the cognitive system can observe changes in the world, check them against a memory of what the world should be like, plan to adapt behaviour to effect a change if required, and then act on the environment to actualise this change. Part of the actual practice of engineering design lies in the integration of many kinds of simultaneous constraints to produce a single solution that satisfies (or *satisfices* - Simon, 1981) the most acceptable proportion of the constraints (in terms of goals and sub-goals) placed on the design as specifications.

### 4.3.5 A cognitive architecture for engineering design systems

The organisation of engineering design within the construction industry needs to be made clear, so that the rich, finely detailed field studies can be interpreted in the light of its macroscopic features - the high level structures that determine goal setting, and the setting within which the detailed elements of activity take place. This will involve the specification of the resources available to the design workers, as well as the constraints incumbent on the designers. Specification of these features of design is performed in an examination of the cognitive architecture of the design setting, placing it within the context of the construction industry. The engineering design process in construction is examined through Marr's framework for cognitive adequacy (1982). This will allow the distributed cognitive architecture of the engineering design process in construction to be fully specified in the analysis.

#### Computational description

The computational description involves specifying what the designers are trying to achieve. It does not involve a close examination of the exact mechanisms used, and simply specifies the most basic of the constraints on the design process. Nevertheless, engineering processes are hard to describe without taking a Western, mathematical perspective because this has become the dominant tradition in design work.

Designing construction through the engineering method involves initial identification of the need for a structure. This is followed by a description of the physical form of the site, the requirements of the problem holder (the client) and restrictions placed on the designers by the materials and other resources available, all of which place constraints on the possible actions that can take place in this problem solving activity.

In navigational terms, a computational description of the problem faced by the navigation team in a 'fix cycle' is that of locating themselves in two dimensional space (Hutchins, 1995a). In design however, the problem is more diffuse because of the ill-structured state of the problem. This involves 'satisficing' so that multiple and possibly conflicting constraints must be satisfied with the limited resources available (such as time, skills, capital and personnel). No structure can be identical with another, so any definitive computational description is at best vague and context dependent. The most specific definition of *what* engineering design in construction entails is given below:

> to plan modifications to, or the novel development of a physical structure within the locally determined constraints within that setting.

Essentially, the constraints, whilst not being fully specifiable, can be broadly (and non-exhaustively) considered under the areas of health and safety requirements, environmental and planning legislation, eventual function, aesthetic requirements, the properties of the construction materials, the technology at hand, time available, labour skills, and financial restrictions. Many of these constraints are interrelated so that change to one affects the operation of others.

**Representational description**

This involves a description of the representations that the designers in the engineering process have available to achieve the computation described above. Representations are propagated through the engineering design system to effect (cognitive) change to the state of the problem solving system. The main representation that moves through the functional system in construction is 'knowledge'. Knowledge includes facts that are known to be true (whether proven or socially constructed), which have existed prior to the design itself, or have been created during it. This knowledge can take many forms: it can exist as mathematical formulae of material tolerances, recommended or legally required standards (such as ISO standards), or they can be mathematical systems themselves (such as the Arabic system of numerals).

Mathematics is a form of representation used to transform other representations; engineers attempt to reduce the human element of subjective judgement by formalising as many of the features in design problems as possible. Mathematics is a method of generating conclusions independent of interpretations (Stewart, 1996), and these representations of reality allow the world to be abstracted into simple components, for example, in judging the forces exerted on a structure with known physical properties. It is therefore a common language used for knowledge representation by engineers.

Whilst abstract mathematical representations of the world are occasionally used to represent spatial reality, more often other methods are chosen. Two methods in particular are used by the construction community. Verbal and textual language is commonly used, and may be implemented in many forms of representational media. Representations can also be represented graphically, again with many possible implementations, as sketches, various forms of drawings, or computer visualisations.

The key graphical representation in the engineering design process is the drawing. The drawing is a means of representing objects that allows computations to be performed on the represented material. This represented material can map well onto the physical experience of reality (Hutchins, Hollan and Norman, 1986). In some cases, drawings may appear in a similar form to the eventual reality (as in architectural drawings) whilst in other cases they may be more abstract (as in symbolic electrical drawings). The computational nature of the drawing lies in its representation. As an 'analogue' representation (Woods and Roth, 1988), the drawing allows design computations to be performed without recourse to complex mathematical transformations. For example, the width and height of objects represented on the drawing can be contrasted with one another through simple visual comparisons, or the use of a set of compasses. Drawings also represent spatial features of the world in a similar, spatial format. This property means that visual comparisons can be made between reality and the represented information. However, this is not possible when comparing real world, spatial information to its expression in an algebraic format (semantically identical, but syntactically different from a drawing, ibid.), which would require several computationally complex re-representations until the two could be directly compared.

Cross (1989) notes that design separates the planning of an activity from performing it, and that this depends partly on the human ability to visualise things internally, but perhaps more importantly, through making external visualisations in artefacts (ibid.). However, the structure of these external 'visualisations' also allows other people involved in design to understand the state of the developing design. This is only possible when the representation is understood by all of the participants: the representation must carry with it a commonly interpretable visual 'language'. A common understanding is usually achieved through either using a learned codification scheme, such as electronic circuit designs, graphs or maps that incorporate universally understood symbols (to the user group), or through symbols that carry the representation in a 'natural' way, such as a naturalistically rendered sketch. A combination of representational forms is often possible within the same representational media, so for example, textual representations can be mixed with more tangible, naturalistic representations.

Where agents do not share specialist knowledge to interpret complex design scenarios, representations can be used as 'boundary objects' (Star, 1989). One such boundary object is the engineering drawing (Henderson, 1995). The drawing acts as a visual representation that displays the relationships between entities in the designed system. Boundary objects therefore reduce the need for computational complexity in individual agents, because they do not *need* to understand the computational work applied in the construction of the representation, only its eventual function. The drawing can therefore be used as an object in a complex serial process, where it is the output of one process and the input for another. This is elaborated in the fieldwork.

**Implementational description**

In the cognitive description of a functional system for engineering design, the implementational level comprises of the ethnographically informed component of the research. This involves descriptions of the design group structure, how the representational media are transformed to perform the computational functions of engineering design, and how the design workers co-ordinate their ongoing activities.

Collaborative design work is mediated by communications in the form of representations transmitted between designers, in which they pass information to others and respond to incoming information. Each individual has a large range of media with which to communicate (the range is determined by the environmental situation) and must choose the most appropriate in the given circumstances. Transmission of the representation between designers involves a change in the state of the representation, and thus transforms the information represented in it. Within a work system, these transformations are used to process the represented material, successive transformations resulting in problem solution (Simon, 1981).

Representations are transformed through 'co-ordination events'. These can occur when one representation is in a form that can be acted upon to generate a new representation. One common example of this is that it is impossible to directly compare a drawing and a letter relating to that drawing without some form of mediating event - usually in the form of an engineer reading the letter, going to the appropriate drawing and using their situation specific knowledge and their encultured knowledge to interpret both of the representational forms, so that the text can be re-represented into graphical terms. This may result in a change to the drawing, a new letter being written, or in transforming that designers internal knowledge (itself a representation, although not visible) of some feature represented in that drawing. Transforming a design representation across different media thus performs information processing on that representation. This cognitive activity can however, only be interpreted at the systems level: no design related information processing has occurred within the individual. Only when the larger group of person, artefact and activity are considered can these transformations be understood as constituting a 'design' activity.

### 4.3.6 The role and organisation of ORGANISATIONS

A feature of engineering systems is that they organise their behaviours so that agents in the system know what their basic responsibilities are, and are made aware of the procedures that they are expected to follow. Procedures are normative descriptions of the group's work. In Hutchins' study of navigation systems, these took the form of the 'Navigation Department Watch Standing Procedures'. In the engineering companies observed, these procedures were documented in the organisation's internal quality assurance systems, which set out the responsibilities and roles of the agents within the system. In addition to this, some construction project contracts may specify how the inter-organisational collaboration is to be maintained, in the particular forms that communication should take.

It is important not to confuse the idea of the organisation of work with the organisation as commercial entity. The distinction between an ORGANISATION (a commercial entity, from hereon, capitalised) and organisation (relationships between individuals) is important (Rosenberg and Hutchinson, 1994), because workers can configure an organisation across ORGANISATIONS. The organisation of the ORGANISATIONS with respect to one another can be generated explicitly in quality assurance system or contractual details set out prior to a project, or it can develop implicitly. This implicit organisation can occur through the process of enculturation in training, or it can develop as a consequence of working closely with co-workers over an extended period of time.

The organisation within an ORGANISATION is not obvious from the examination of an ORGANISATION'S official hierarchy. These hierarchies can misrepresent the true organisation of work because they simply describe managerial roles and salary based information. Work itself may not be organised according to this structure. Additionally, within an ORGANISATION, there may be multiple projects, and each project may be organised differently. It is therefore important to differentiate between the work as performed, and how it is described.

## 4.4 Data, theory and systems development

### 4.4.1 Bridging the gap

The research carried out in the thesis begins with a framework in distributed cognition, and conducts field studies using the framework to focus data collection. The data collected is then analysed using the framework, to specify the mechanisms used to co-ordinate the collaborative activities between design workers. This analysis is then applied to the area of systems development, in order to provide support in the development of technology to support engineering design work. The following section examines the relationship between data and theory, exploring the interrelationship between them, and investigates how this understanding can, and should be, applied to the development of technology.

### 4.4.2 The role of theory in research

Theory plays an important role in structuring our understanding of the results of data collection and it allows us to make causal links between phenomena. As Hermann Hesse states in The Glass Bead Game, 'Every science is, among other things, a method of ordering, simplifying, making the indigestible digestible for the mind' (1943, p. 168). Theory therefore plays the role of determining what features of the world have ontological significance, how to frame our research questions, and what data to attend to. These issues are addressed within the thesis, where, in attempting to describe how design is organised, the enormous volume of potential data available and collected must be organised in a way that provides enlightenment on the phenomena observed.

Following the descriptions of the work conducted by the design teams, the thesis will attempt to demonstrate the relationships between distributed cognition (the analytic theory), our understanding about design in the construction industry (the domain theory) and the data collected in fieldwork, bringing them together into a new and integrated understanding of design. The relationships between these three areas are elaborated on below:

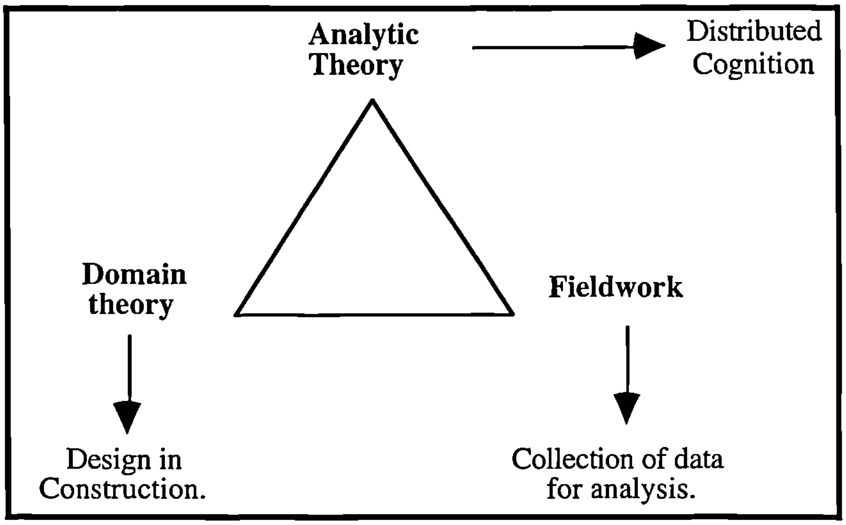
**Analytic theory** - this is the role of distributed cognition. Distributed cognition forms the theoretical basis framing the analysis. It provides a framework that structures the fieldwork into a form that can be used to describe the salient features about the co-ordination and performance of work.

**Fieldwork** - this is the form of the raw data collected from the field. The fieldwork is informed by the analytic theory which determines its focus on the features of relevance to distributed cognition: representations and processes. It tests the link of relevance between the analytic theory and the domain theory.

**Domain theory** - this is developed from bringing together the analytic theory with the fieldwork for analysis. It explicitly identifies the mechanisms co-ordinating the collaborative aspects work described in the fieldwork within the analytic framework of distributed cognition. The aim of this research is to develop a rich domain theory of design in the construction process, and describes how design operates at a social, cognitive and organisational level. The intention of this is that it can be used to inform system developers about information use within settings.

The relationship between them is shown in fig 4.1.

fig. 4.1. Relationship between analytic theory, domain theory and fieldwork.




An important point to note is that the domain theory develops in parallel with the fieldwork, as interpretations (or 'working hypotheses') are made about behaviour and examined in more detail. This one of the features of the ethnographic approach - hypotheses are generated and developed in conjunction with the data collected.

### 4.4.3 Technology transfer and the function of the analyst

Workplace studies are one approach to examining work systems, and that which is selected within this thesis. However, the function of workplace studies is itself disputed (Plowman, Rogers and Ramage, 1995). In some cases, fieldwork is presented as if systems design was completely divorced from it (e.g. Bowers, Button and Sharrock, 1995; Symon, Long and Ellis, 1996). Other approaches have attempted to be more pragmatic, in using the fieldwork to show where problems occur in the performance of work (Rogers, 1992; Nardi and Miller, 1989) and what sorts of things will need to be supported when moving from the real world to the virtual, or electronic world (e.g. Pycock and Bowers, 1996; Bentley *et al*, 1992; Heath *et al*, 1993; Halverson, 1994).

This thesis does two things in its approach to informing developers about the research domain:

1. It describes collaborative work practices that will need to be supported when moving the representation from a real to an electronic environment.

2. It describes the operation of the underlying mechanisms of behaviour between the distributed designers. This level of explanation is relevant to design because technology does not simply augment existing work practices to make them more efficient (speed, accuracy, pleasurable interaction); rather, it can change existing work practices so that simple descriptions of work practice will not always be applicable to the new situation.

Both areas are covered in detail in the fieldwork, which describes current work practices and in the mechanisms underlying collaborative activity in the computation of design solutions.

Whilst there is currently no way to directly transform descriptions of work into specifications for technology development, it is possible to describe the work observed so that suggestions can more easily be made. The fieldwork and analysis described in the thesis performs this, describing the co-ordination of collaborative work in terms of its processes and the representations used; issues of information transfer are picked out (and antithetically, information bottlenecks), and the information inputs and outputs to phases are made explicit. These are the critical areas of collaborative work that determine the performance of the design activity. These process based, transactional descriptions of work allow system developers an informed choice in how to change the management of the design process through the introduction of technology.

In many cases, the fieldworker cannot directly determine the form of the technology being developed. The experiences of social scientists working directly with technology developers differs significantly from situations where fieldworkers operate in 'armchair' design situations. In multidisciplinary research and development, there is an interactive and iterative element that cannot exist in uni-disciplinary situations. In current of interactive software development, social scientists are rarely the central focus of development activity, but act as a knowledge resource. Fieldworkers are considered to be the experts in the domain of interest, and can be "grilled" by the developers who may be highly proactive in eliciting design related information. Fieldworkers may be used as proxy users for determining what users would do in particular situations, and they may be asked how they believe users would make use of the proposed technologies.

### 4.4.4 From fieldwork to technology development

Transforming of the findings of the study into specific design recommendations is problematic: the raw data from the field has to go through a series of modifications to reach a stage where it can be given to system designers and used in developing appropriate assistive technologies. These stages are shown below:

i. Observed action (data collection)

ii. Described action (fieldwork representation)

iii. Analysed action (mechanisms of co-ordination)

iv. Design recommendations for the support of action

v. Development of technology to support action

The stages following the second or occasionally the third stages are not normally areas that social scientists attempt to enter (e.g. Suchman, 1987; Bucciarelli, 1988, 1994), although interdisciplinary work in the field of CSCW has attempted to bridge this divide. Social science has developed methods of data collection and analysis that can describe activity, yet these cannot be directly linked to the development of a technology. An element of creative interpretation is required in looking at areas of the fieldwork and analysis, to see where existing technologies could be introduced and new technologies designed to support work. The development of technology viewed from this perspective is also a creative process.

## 4.5 The framework for analysis

### 4.5.1 Data collection in DC - methods and application

This section documents the field study designs with reference to the method of data collection (ethnographically informed fieldwork). It examines the relationship of the fieldwork to the analytic theory, showing how the data is analysed within the framework of distributed cognition, and its application in the development of a coherent and useful understanding about engineering design (the domain theory).

The ethnographically informed method of fieldwork (section 3.6) is a means of physically entering the expanded cognitive system and exploring the emergent behaviours arising from the interactions of persons and the environment that their activities are situated in. The data collected from the ethnographic approach can be combined with a distributed cognitive framework allowing researchers to study the representations and processes that the designers use, and their organisation in the functional system (through the distribution of labour). In doing so, such an analysis provides a representation of work (Suchman, 1995) by revealing the practices that actors participate in. The representation of work that the analysis provides can be integrated into a cognitive engineering approach to system design, so that designers can make informed choices about how to go about redesigning the systems that they intend to support.

To avoid the problems associated with adopting the normative perspective of work (section 3.6.2), rather than examining the work as enacted, the research attempts to develop a rich description of the setting through several different data sources. Thus, the fieldwork documents the situated activities of design systems through shadowing, interviews, document collection and ethnographically informed observations. Data about the engineering designers, the task, the tools used, and the organisational context of their activity is collected, following the information input and output pathways of the functional system.

**Interviews:** The focus of the interviews is on identifying the participants involved in the functional system, who the interviewees are in close communication with, what tools they use in the performance of their work, what and how these tools are used in communication, the problems that they have in performing work, and how they gather work related information from the world around them.

**Document collection**: This centres on documents involved in the design process - drawings, sketches, notes and letters, faxes, schedules, contracts, forms, and so on. These helps to build an understanding of the background context around which work is performed and in determining the range of artefacts used in the design process. The documents and their content are used in generating interview questions, but also in showing how representations within these artefacts are transformed, by cross linking them (data triangulation). This involved looking at the letters accompanying particular drawings to see what changes the documents had undergone and why this had been necessary.

**Observational study**: The observational study involved watching, listening and recording the behaviours of the design workers as unobtrusively as possible. This is intended to give an idea of the work involved, the management of this work, the communication methods used, and problems with communications. The material is used to generate questions for interviews and to provide data with which to illustrate how representations are used to co-ordinate the participants and in the performance of information processing.

The analysis involves mapping out the information flows (the chains of representational transformation) through the organisational structure, identifying the sources and sinks of this information, the tools used to manipulate and transmit it and the 'chains of command' initiating activities.

In a distributed cognitive analysis of collaborative design, the methods of analysis used must be able to track the 'states' that the design goes through. Representations of a design may exist simultaneously in a number of places, in multiple formats and representational types; its forms can include models in peoples heads, text, graphical representations (in sketches and drawings), and numerical representations (as technical specifications). Design information does not have to be logically consistent and may even be contradictory, because it is in a constant state of flux and iterative development. As such, tracking the 'design' process is something of a misnomer, because the representations of design can multiply (e.g. through photocopying), change form (a representational state change, e.g. paper to floppy disk), or 'die' (as it is discarded or completed). It is possible, however, to chart the progression of a design through changes in its representational media. As DC theorists postulate, these 'flows of information' constitute the cognitive processing element of an activity. The mechanisms by which this information is propagated and co-ordinated forms the computations performed by the functional system.

In navigation it makes no sense to say that any one person is steering a ship, because control is determined by the activities of a team. In the same way, no one person is involved in designing a construction. The adoption of DC as an analytic framework therefore introduces and defines a new concept of 'design' in the process of engineering: it is an emergent process arising through the social interaction of multiple actors in a setting rich in representational artefacts and other organising resources. The thesis applies ethnographically-informed data collection techniques to discover how engineering design workers distribute their labour and co-ordinate their work with one another. It draws from, and develops, an analysis of design based on the investigation of external representations and processes used in the performance of work by examining the design artefacts, the social processes and ORGANISATIONAL procedures, and the settings within which design occurred. Following this, it will take the descriptions of design, and use these to examine areas that are felt could be improved through the introduction of technology. These are further developed these into a set of design recommendations for the deployment of appropriate technologies into the engineering design process.

### 4.5.2 Elements of analysis in engineering design

The focus of data collection in distributed cognition is based on the elements of its analysis - the representations and processes that perform information processing in the functional system. The emphasis of data collection thus falls on the representational media - artefacts - that the representations are embodied in, and the processes acting on these artefacts. The elements of analysis therefore include the participants, the tools that they use in their work, how these tools are used to co-ordinate their activities, and how their context provides resources from which they can draw to perform work. The processes of work, determining the relationships of people, and artefacts, with respect to their context need to be clearly described, because they determine how the representations are brought together and transformed from a representation of a design problem to generate a solution. The participants need to be described in terms of their contribution to the design process as a whole, and to the specific activities taking place within the process - they are not individuals acting alone, but act as processing units in the computational process that makes up design. Three elements therefore form the focus of enquiry: participants, tools for co-operation and context.

### 4.5.3 An integrated framework for analysis

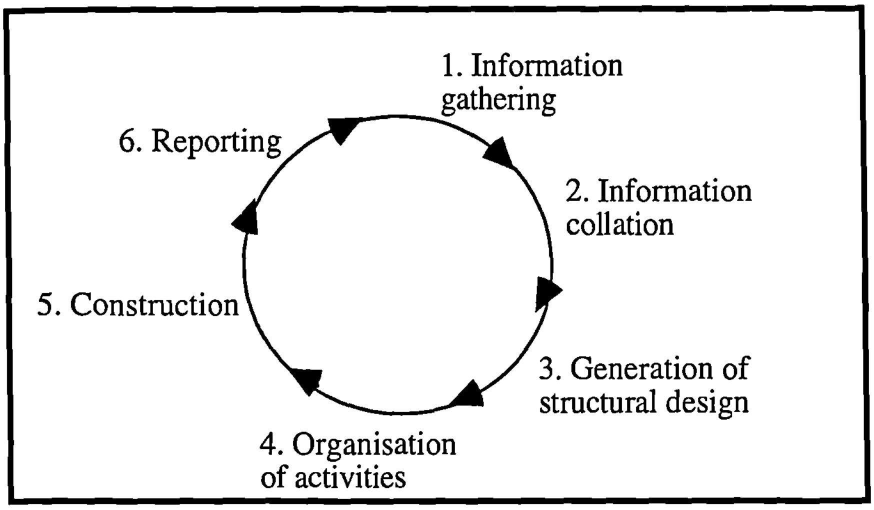
To investigate the collaborative performance of design within the construction industry, the three areas that make up the thesis, in data collection, analysis and their use in systems design need to be made explicit. Each of these is considered in turn below, and are used to guide the research in the following chapters.

**Data collection and 'the cycle of design'**

The focus of data collection in the fieldwork is guided by the distributed cognitive framework on three basic elements: people, tools (or, artefacts), and context. Data collection in the examination of engineering design in the construction industry attempts to describe the task performed by the functional unit in these terms. The method applies the ethnographic framework to describe how people interact, both directly, and mediated through artefacts. The data collection therefore attempts to describe the activities performed by the functional systems as they are performed within the *context* of the setting that they take place in. Following in the ethnographic tradition, work is described in the terms used by the participants themselves, which has resulted in the fieldwork being described in a narrative form, the 'cycle of design', breaking the design process down into six phases.

The cycle of design is a device that was used to add a structure within which to organise the data collected. It develops along a temporal dimension, as the design moves through a number of stages that were identified through comments made by informants. These stages were both alluded to in the normative procedures prepared by the ORGANISATION, and observed in practice. In the fieldwork, each phase is structured as if it were a distinct *functional system*, the outputs of which could provide the inputs for the next phase in the cycle. This is shown in fig. 4.2.

Fig. 4.2. The cycle of design




These phases are general and were said to apply to all construction engineering projects. In each phase, documents were created and changes recorded, demonstrating when each design phase had been completed and when the next could begin. These phases were similar to the cycle of cognition and perception in human activity: events in the environment are perceived (such as light being reflected in the eye or air pressures differentials), corresponding to *information gathering*, and these events are cognitively processed into elements with meaning (transformed into visual images or sounds), analogous to *information collation*. The information is then processed so that an appropriate course of action can be taken, corresponding to *structural design*, in generating a plan (such as avoiding the stimulus by walking away). This plan is transformed into physical actions (such as instructing the motor system to move various limbs), as with the *organisation of work activities*, and the actions taken are monitored through feedback from the motor system, in *reporting*.

The cycle of design is not intended to differentiate between *distinct* components of the design process, but as a means to bring order to what is a highly complicated and interrelated set of practices. The cycle is therefore a rhetorical device that is intended to clarify a diverse set of data into something more manageable. It is not possible to say that design always occurs in the way described; it is not possible to say that the processes are distinct from each other; nor is it possible to say that the cycle progresses in a particular direction. Indeed there may be other ways to describe design - and this is only one of them. However, the cycle does provide a powerful narrative structure within which to frame the material collected into a coherent story that is relatively simple to follow.

**Analysis**

The focus of the analysis is on how design representations are transformed in the functional unit under examination. This will involve examining the underlying mechanisms behind the co-ordination of the elements described in the data collection. These areas will be investigated to see how communication is used to co-ordinate these activities, how the media of the representation helps to determine their use in information processing, how an effective division of labour is organised and maintained, and how context is used as a resource to structure activity in the work settings.

**Supporting systems design**

The analysis of engineering design has implications for the development of context-sensitive technology because it demonstrates how the component parts of the functional system interact with one another. The explication of these interactions has potential in clarifying how novel technologies might be introduced to augment the processes described without disrupting important, existing patterns and practices of work.

The analysis of engineering design provides a rich description and explanation of the mechanisms of collaboration within the domain. However, it is recognised that this understanding cannot easily be transformed into well specified technologies. Nevertheless, suggestions for technology that could augment the process of design can be generated. Drawing from the analysis of the mechanisms used in the performance of engineering design work, it is possible to show where technologies could support these processes. Suggestions from material generated in the course of the thesis the have been confirmed as relevant to technology developers through their adoption in the CICC project (Perry *et al*, 1997), although the nature of this integration is outside the scope of the thesis. Some of the features adopted in the project are however described, where they illustrate how this approach can be applied.

### 4.5.4 The format of the field studies

The structures of the groups that will make up the function units of design in the construction organisations examined in the fieldwork are described in chapter 5 (and Appendices A and B).

The results of the field studies are grouped together into behavioural features that are perhaps unfamiliar to ethnographers, and in particular to ethnomethodologically oriented ethnographers (section 2.4.3). It is perhaps pertinent to note that there that there is often a great deal of confusion over this point; in CSCW, ethnography is often confused with ethnomethodological ethnography (Shapiro, 1994). The reason for this change in emphasis is that the study is directly aimed towards helping systems developers. These developers will use the field studies of collaborative design to support design engineers with technology. However, it is not simply enough to provide a representation of the fieldwork and to let the developers use this as a guide: the fieldworker must provide a representation that is *adequate* and *appropriate* to the needs and requirements of the reader.

There are many ways to represent an ethnography (Van Maanen, 1988) and this thesis aims to present a rich description of a goal based activity for a particular reason, that of systems development. As with design (Rittel and Weber, 1984), there are no 'right' ways to present ethnographic and ethnographically informed fieldwork; there are just good and bad ones. What determines whether the representation of work is 'good' or 'bad' is the use to which it is put; it must be appropriate to the problem for which it is to be used. A central argument of the thesis is that the information processing approach of distributed cognition is an adequate and appropriate means of examining the collaborative engineering design process for use in systems development.

Representations of ethnographic material and fieldwork are fraught with difficulties, in determining what material to present to the reader and how this is to be structured to provide an adequate description of the practices observed, whilst not swamping the text through an overly rich portrayal of the situation studied. This issue of representing the data collected is especially compounded where there is a dichotomy in the methods of representation between systems development and social science. Both systems development and social science have their own means of describing situations, and in an interdisciplinary study, the analyst is caught between these conflicting worldviews. In traditional systems design, the techniques of requirements analysis provide an abstract description of the behavioural phenomena observed, with quantitative data to back up these results. Social science, and in particular the ethnographic studies in the CSCW literature provide detailed descriptions of activity, emphasising the situated and locally organised nature of this activity. An attempt is made to steer a middle path through this minefield in an attempt to provide a description that is both true to the situated nature of the activity yet retains a degree of abstract structure that allows generalisations to be made outside the particular environment observed. This is described in more detail in chapter 5.

## 4.6 Conclusion

Distributed cognition can be applied as a means of examining and analysing engineering design, and can be applied in developing computer-supported co-operative systems to support design work. Whilst engineering design differs to the previous most thoroughly expounded examination of a distributed cognitive system (navigation), it has a number of similarities at an information processing level. Comparison of the two domains shows why previous DC methods and understandings cannot be directly applied to this problem domain, and that a different methodological approach must be used to examine the area of design. To perform this, existing methods of data collection are adapted in a manner appropriate to the setting.

Similar settings could be analysed using the approach outlined in the thesis with the following steps:

1. Identification of the problem faced - determines the goals and boundaries of the functional system to be examined.
2. Performing field studies, looking at the structures of communication within the functional system.
3. Determining the inputs, the outputs, the representational media and transformational processes acting in problem solving from the field studies. This would examine how:
   - the qualities of the media chosen by the participants determine their use in problem solving behaviour.
   - social interactions around the media determine the outcome of changes to the representation
   - ORGANISATIONAL procedures determine how agents interact with the world
   - the setting provides resources for (and constraints on) communication between agents, and agents and artefacts.
4. Fitting the data into the distributed cognitive framework to examine the interrelationships between the component parts and how they produce emergent patterns of behaviour.

The analysis of engineering design begins with a description of the computational and representational properties of the functional system of activity. This details the goal of the problem solving activity and the resources at the disposal of the functional system that it can apply to the situation. Context is selected as an important resource in the performance of design, both for the design workers, who draw information and meaning from their environments, and to the analyst, who must interpret how this is performed by the design workers. For the analyst, context forms a central component in the organisation of activity and it requires detailed examination to see how it is used in the co-ordination and performance of work. How these problem solving resources are integrated together is described in the fieldwork in Appendix A and B, described in terms of 'the cycle of design'. The method by which this was achieved using distributed cognition as a means of directing data collection and representation is described in chapter 5, which highlights the main findings of the field studies.

# Chapter 5

# Data Collection - Collaboration in Construction

## 5.1 Overview

Data collection draws from the analytic theory in the framework of distributed cognition to highlight areas of activity that are computationally relevant to design work. It applies this approach using ethnographically informed fieldwork (chapter 3) to investigate engineering design (chapter 4), through the observed activities on the site itself. The analytic theory was used to select the actions relevant to the performance of the collaborative design activity, and in filtering out features of work not relevant to this perspective. The bulk of the fieldwork is represented in Appendix A, and in the second, briefer and supporting field study, documented in Appendix B.

The fieldwork is itself described in the terms of distributed cognition, with each phase in the 'cycle of design' described in terms of its inputs and outputs, and the representational artefacts and processes that perform the transformation between them. However, the complexity and bulk of the field data means that it is unsuitable for demonstrating *how* the distributed cognitive analysis was applied, because of its ethnographic narrative style. Whilst this form of representation is useful for explaining the intricacies of the settings examined, it is hard to be reflexive about the methods used to obtain this material. In addition, the findings are hidden in the mass of field data. This chapter therefore distils the fieldwork, showing how relevant information about the design process was obtained, and summarising the important findings about the co-ordination of the participants and representational artefacts in the process. The critical parts of research from the field studies are also summarised here. For a fuller picture of the workplace studies, the fieldwork itself should be consulted.

## 5.2 Studying the co-ordination of design work

### 5.2.1 Background to the field studies

In order to understand the elements of the data collection described in this chapter, a brief introduction to the work examined is required. The fieldwork involved the study of a construction company, known here as ConsCo, who were working on a large road building scheme, part of which included a bridge. The initial engineering designs were contracted by a client (the Highways Agency) to an engineering company (known as the Project Engineer), whilst the construction work, known as 'civil engineering' was contracted out to ConsCo. For the purposes of the study, the unit of examination comprised of all of the parties involved in a particular design activity - the functional design system. Fieldwork covered the participation of three distributed units working in ConsCo. In addition, several other ORGANISATIONS also participated in the process. It is important to note here that the *activity* set determined the boundaries of the design system, not the artificial ORGANISATIONAL groupings.

An 'arrival story' of entering the field to study design is documented in Appendix A, to give a flavour of the workplace and to expose the nature of collecting material in naturalistic research. It is important to make the issues involved in data collection clear, so that the fieldwork can be evaluated in a manner appropriate to the methods used.

### 5.2.2 Data collection

Data collection focuses on the mechanisms for co-ordinating collaborative work in the domains studied. This forms a resource with which to understand the work of the design workers observed. The key to understanding the function of distributed cognition in the fieldwork is that it directs attention onto the information processing aspects of work activities and exposes the mechanisms involved in the co-ordination of activities and in the organisation of the task. These mechanisms are described in terms of co-operative activity, which formed the basic unit of analysis in the field.

Data collected in the field is broken down into the elements of analysis proscribed by distributed cognitive analysis (from chapter 4), through the computational characteristics of the process. The descriptions of work presented here therefore include work documented in terms of its cognitive features: the inputs, outputs, processes and representations that pre-exist and emerge through the performance of work (figs 1a and 1b, page 6).

The activities involved in collaborative engineering design in the construction industry are considered in more detail through an examination of:

1. The *task* - The primary task is described in terms of its goals and resources. The resources included the people, artefacts, and the relationships between them

2. *Organisational structure* - The organisation of construction activity, and the monitoring of, and accountability for these activities.

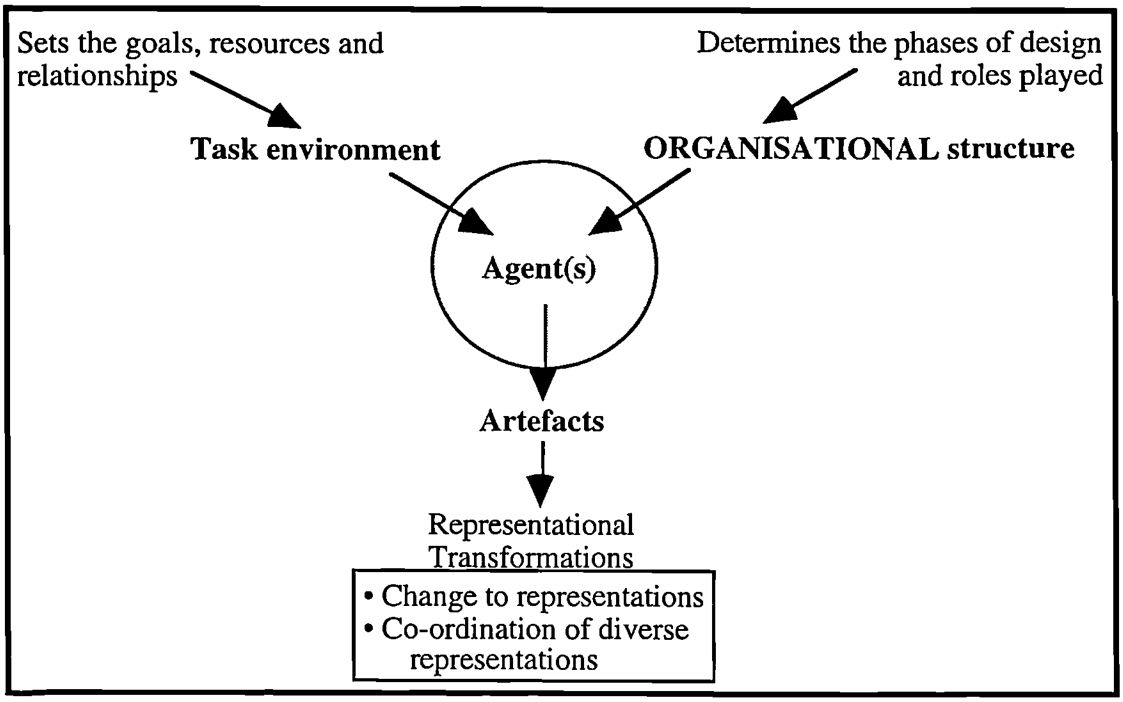
3. *Transformational work* - The inputs and outputs to the functional system and the transformations on the representations in information processing.

4. *Collaborative work* - The communication processes involved in the co-ordination of representational transformations and collaborative activities.

This structure explicitly and directly links the cognitive basis of collaborative work to the field studies in the generation of a domain theory. The examination of the task determines the resources available to the functional system that can be used in achieving its goal. The organisational structure determines how the resources are explicitly structured and their relations to one another. The transformational work examines the nature of the information processing activities that the functional system performs to accomplish the task. The collaborative work involves the co-ordination of the elements of the functional system, so that the transformational work on the task can be carried out by a distributed group of agents.

The interrelationships between the components described above are expressed in the diagram below, which provides an explicit, if simplistic, representation that links the method of analysis to the framework of distributed cognition (fig. 5.1):

Fig 5.1. Interrelationships between the analytic elements of the field studies




The diagram shows how the physical context (the task environment) and the ORGANISATIONAL structure act as constraints on the behaviours that can be performed by agents on the artefacts that they use. The shaded area represents the co-ordination that agents perform, bringing together the information from the environment and the ORGANISATIONAL structure, and acting upon the artefacts of work. Actions on artefacts result in representational transformations on inputs (either as change to representations, or through co-ordinating the use of several representations) into outputs.

## 5.3 The task - construction work

The distributed cognitive framework tells us that the task can be broken down into goals, resources and relationships. These are the 'given' element of work, which is manipulated by transforming the start state into a goal state, and the resources and relationships which structure the *overt* organisation of this work. To demonstrate how the task was structured, the example in Appendix A of ConsCo is examined in terms of these elements.

### 5.3.1 Goals

The goals of design in the work of construction involve determining what the problem is and specifying what the desired result of change will be. In the example of ConsCo, the primary goal for the construction team was to construct the given designs as cost effectively as possible, conforming to the drawings, within the safety requirements, legislation, industry standards and other stakeholder requirements. To perform the task, the design workers had to adapt information from designs of the final road structures (in the drawings), to develop a means of erecting them: these short-lived structures are known as 'temporary works'. The temporary works drawings have to detail how the structure of the original designs is to be erected in practice. These include the supports to be used, the placing of concrete moulds, the location of the haul roads to supply the site, and so on. Once the temporary works structures are erected, the permanent structures can be built, involving the placement of steel reinforcement and pouring of concrete.

Determining the goals is important in performing an analysis using distributed cognition because goals determines the computations that will have to be accomplished by the functional system. The functional system must organise its activities so that the (design) task performed achieves its goals, within the constraints set by the resources available.

### 5.3.2 Resources

The framework of DC requires that the resources available to the functional system are made clear. In order to begin the design and construction process, resources had to be put to work. In the design system observed at ConsCo, these resources comprised of agents and artefacts.

The agents involved in the design process included the originators of the road design ('the Project Engineer') and their site representative ('the Resident Engineer'), the members of a construction team, a 'temporary works' design co-ordinator, and a 'temporary works' design engineer. Other groups were involved in the process, most notably an environmental agency, and a railway operator, over whose tracks the bridge crossed.

The initial design artefacts included the Resident Engineer's design drawings showing the final structure of the built design, including the materials to be used, placement of the steel reinforcement, location of piles, and structural tolerances. The construction team had copies of these drawings.

Other artefacts that were used in the design process enabled the design workers to communicate over distance. The technologies for communication were numerous and diverse, including those explicitly recognised as communications technologies, such as telephones and fax machines, and those used as a means of communicating non-verbal information, such as the drawings and schedules. In addition to these methods of communication, method statements, risk analyses, sketches, post-its, the 'weekly work schedule', letters, and works records were used. The 'works records' functioned as the site diary: the official record of activities on the site, comprising of site instructions, site records and requests for information. All of these artefacts bore representations that could be communicated between the collaborating actors involved, allowing them to perform their own individual tasks as well as achieving the high level design goal.

An explicit description of the construction process was available to the construction team, in a manual known as the 'Contract Quality Plan'. This document described what operating procedures to perform at any given point in the design process, although in reality, few people said that they had read it, and it was several months out of date. The procedures involved in the generation of temporary works were also described in a document: the 'Planning and Temporary Works Handbook'. These procedures explicitly set out the relationships between the parties to temporary works design, their responsibilities and proscribed methods of work. However, it was rarely used and was also several years out of date.

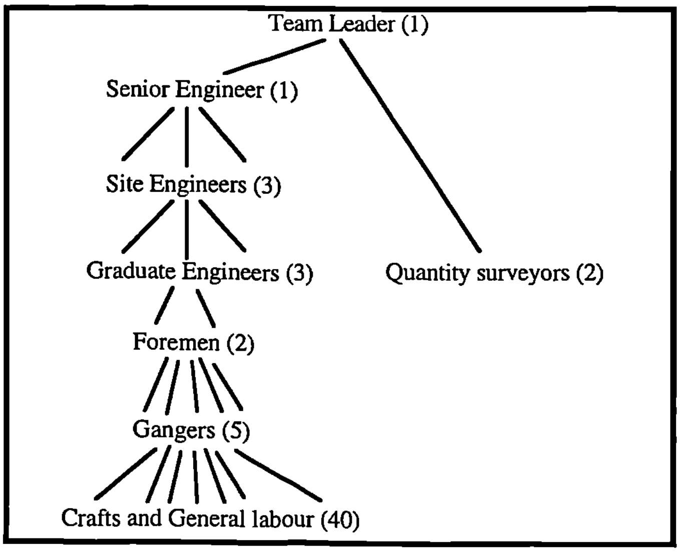
### 5.3.3 Relationships

The relationships between the resources determined the configuration of the functional design system. On the road building project, there were several such structures, within and across ORGANISATIONS, and these are described more fully in the fieldwork itself (Appendix A). These relationships were identified from interviews and from the Contract Quality Plan and the Planning and Temporary

Works Handbook. Spatial relationships between individuals were determined from the observational work.

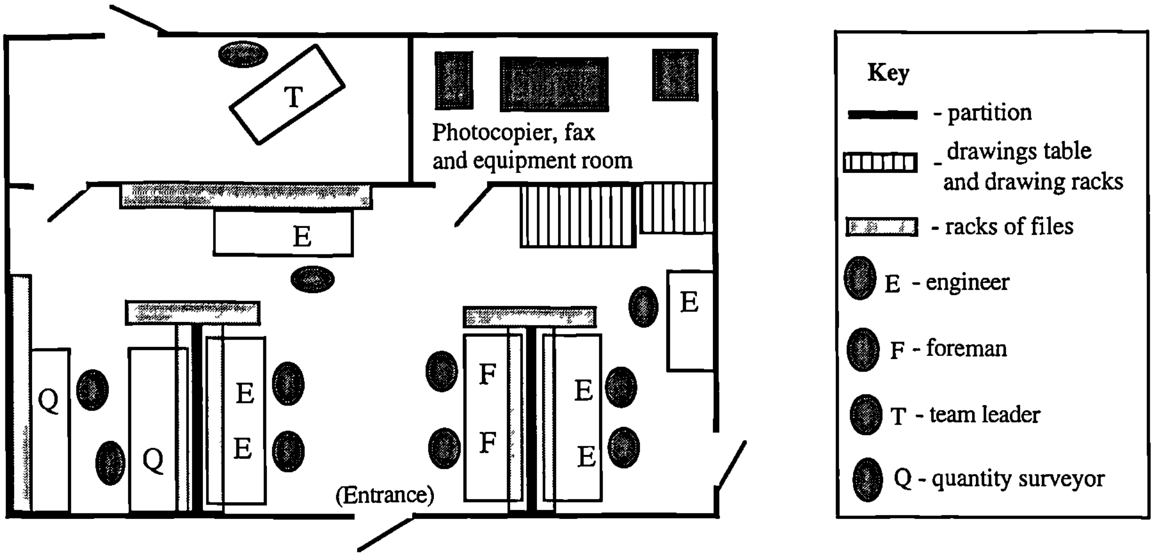
The ORGANISATIONAL relationships between the construction team members was organised in a hierarchy, which included a team leader, seven engineers (one senior, three site, and three graduate engineers), two foremen (senior work supervisors), five gangers (junior supervisors), the craftsmen and general labour, varying around forty in number (see fig. 5.2). Two quantity surveyors, similar in rank to the graduate engineers, reported directly to the team leader. Only the team leader and senior engineer had an overview of the responsibilities and tasks performed by the rest of the team. In general, the labourers were only partially aware of the responsibilities of other people, although they were aware of the procedures relating to their own work. This hierarchy therefore determined tasks that individuals were involved in and responsible for. It provides an insight into the delegation of work, and how knowledge about site conditions was passed around the team.

fig. 5.2. Hierarchy of seniority in the construction team.




The construction team was located in a satellite office, and distant to the main site office. This satellite office was used by the engineers and senior construction personnel, and was laid out in an open plan style (see fig 5.3.). The diagram demonstrates the visibility of the team personnel within this confined space, and shows how they had access to resources, including the design artefacts (drawings and text files).

fig. 5.3. Layout of construction team office




The labourers worked on the site ten minutes away along a half mile stretch of poorly maintained haul road, accessible only by foot or four wheel drive transport. The role of the foremen was to make sure that the temporary works were being constructed according to the drawing designs. The gangers worked more closely with the labourers on the site and were thus able to manage work on a moment-by-moment basis. The gangers and foremen had access to radios to each other questions, requisition materials, or locate people. They could also drive their four wheel drive vehicles back to the office to engage in face-to-face meetings.

When new temporary works designs were required, it was the task of the senior engineer to collaborate with the design co-ordinator to generate a design specification. The role of the design co-ordinator was to mediate communication between the construction teams and the temporary works design engineer, who would transform the specifications into a design solution. This involved passing the construction team's requirements on to the design engineer (who was remote from the site) and managing further communications between them. The design co-ordinator therefore acted as a conduit for filtering and passing information between the two remote groups.

The resident engineer (RE) was employed to ascertain that the construction work was being performed in accordance with the designs, and the quality standards specified in the contract between the client and ConsCo. Their work was split into spatial areas, each supervised by an 'assistant section RE'. The assistant section RE had a 'man on the ground' checking standards and watching the work as it was being performed, known as the 'clerk of works'.

Materials suppliers were also involved in the design of the construction process when providing equipment and plant. The materials most important to the temporary works process were the 'falsework' and 'formwork' for supporting and moulding the concrete structures. The suppliers of some specialist materials were also involved in producing designs for temporary works involving their materials, because of their skills and experience in using the products. These 'supplier designs' could affect other designs in unexpected ways, because they could change access routes, require work to be done in a specified order, or affect the 'critical path' of the project.

The other groups whose approval was required for work to proceed included the railway operating ORGANISATION and environmental agency. The railway operators had a particular concern that material would fall from the bridge onto the trains passing below. These were charged with checking on construction to ensure that the work did not disadvantageously impact upon their operational areas. The railway operating ORGANISATION needed to check that the structural work did not represent a hazard to their train services on the railway line, and the environmental agency had to ensure that work did not result in environmental damage or pollution to the watercourses. In any instances of failure to follow previously agreed upon methods, they were able to demand a halt to work until the situation was resolved with a redesign or change to the construction methods used.

An example of the role of these groups in a situation where these inter-ORGANISATIONAL controls failed is given below, which demonstrates the relationships between these groups:

On one occasion, the team's carpenters had run out of planks to build a supporting platform over the bridge. They did however, have thicker planks available. Rather than ask if these were usable, the craftsmen took the initiative, reasoning that the planks, being thicker, would be even safer than the originally designated materials, and they used these instead. However, this solution was not as simple as they had imagined: because the planks were thicker, they were also heavier, and placed a greater load on the structure. This was above its projected loading tolerance.

When this was noticed in a routine check by staff from the railway operator, a formal complaint was made to the team leader, who decided to have the strain tolerances recalculated for the new materials. He communicated the complaint and the properties of the new material to the temporary works design co-ordinator; the design co-ordinator passed the problem on to the temporary work design engineer, who calculated that the loading factor was dangerously high. This information was communicated back, and the structure had to taken down and rebuilt with different materials. This was heavily time-consuming, and because it fell across the critical path of the project, it delayed other aspects of the task and increased the overall expense of the construction work.

## 5.4 Organisational structures

### 5.4.1 Phases of design

The activities that the design workers were involved in were highly complicated, and were simplified in the fieldwork through the 'cycle of design' (section 4.5.3), in which the design process was broken down into six component phases. Below are brief explanations of the cycle in the context of temporary works design relating to the bridge deck of the road building project:

1. *Information gathering* arose out of the day to day management of construction activity. General information was gathered by the people working on the site, and of any problems or difficulties that they had in performing of their work. It also involved searching out discrepancies between the built structures, and the plans (the structural designs and time schedule). This involved a constant, ongoing process of collecting general information about the state of the site that continued in parallel with the other phases.

2. *Information collation* involved transforming knowledge about the state of the site into a physical representation of the temporary works problem. This involved determining the relevance of the information gathered, and relating it to the design problem to enable basic specifications to be set. Information about the site was distributed over several areas of the site and a range of personnel. This information was then collected into a coherent and organised form relating to a particular design feature. The end result of this was a 'design brief', the first unified representation of the temporary works design problem.

3. *Structural design* involved clarification of the design problem and matching this to the resources available. The goal of this phase was to transform the problem into a solution matching the requirements of the design brief. This involved the production of design drawings, checking that the requirements of the various parties involved were met, and transmission of the drawing to the construction team.

4. *Organisation of Site Activities* involved the construction team planing how to erect the temporary works structures by determining the local resources available with which to implement the proposed design. Construction resources had to be organised, including the ordering of materials and plant, breaking the drawings into a schedule of activities that could be performed by the individual team members, and determining an order for erecting the materials.

5. *Construction* involved implementing the plans for organising the work activities, and transforming the structural designs into a physical construction. It was initiated

by the graduate engineers taking their cue from the construction schedule; the foremen then took over the management of the work, and the structures were erected by the labour.

6. *Reporting* involved checking that the built structures had been implemented correctly in accordance with the designs. Various people examined the built structures, comparing them to the drawings. Reporting activities ranged from simple visual inspections of work to precise measurements using technical equipment. Knowledge from this phase fed back into the information gathering phase for the next cycle of temporary works design activity.

Whilst these phases are described here as discrete, they were not completely distinct. Interactions between phases occurred because the same agents could be involved in more than one phase. Whilst many of the design representations were represented in controlled documentation (e.g. the drawings and design brief), a large proportion of the information relating to the design was retained in the form of mental representations held by agents. This mentally encoded knowledge about the design was *phase independent* and could be applied in more than one phase, where individuals had roles and responsibilities across different phases of the design cycle.

### 5.4.2 Roles and responsibilities

The designers were entwined with each other through their responsibilities to one another. To check that the individuals and groups were accomplishing their responsibilities, a system of accountability and monitoring operated between the units. This occurred within the construction team, and between the construction team and the other groups interacting with them. Accountability for particular tasks was proscribed within official documentation, but it also operated in the social domain, as pressures were brought to bear on people to perform the tasks they had been set. Monitoring occurred through the passing of documentation and in visual inspections of work. Subsequently, data collection on accountability was performed by examining the documents used to monitor design work, and through interviews with staff, to see who they had to inform or monitor. Observational work was also used to see how these interactions took place in a social milieu.

Within the team, members had to report on activities, events observed and of events expected. This took place in weekly team meetings, but also in *ad hoc* meetings, and chance encounters. Team meetings were chaired by the team leader, and all gangers, foremen, senior and site engineers were expected to attend. The graduate engineers and quantity surveyors were also invited, although this was optional. Monitoring of the engineers' and quantity surveyors' work was conducted on an *ad hoc* basis, the engineers by the senior engineer, and the quantity surveyors by the team leader. In many cases, potential problems were volunteered by the personnel themselves.

Alongside the work of construction, the costs of the work had to be controlled; the team's quantity surveyors performed this accounting task through the production of reports on the team's projected and actual costs to demonstrate that work was being conducted cost effectively, and according to plan. The quantity surveyors therefore had to be aware of the work that the team was doing and understand the materials, processes and importance of the construction work.

To demonstrate that the construction team's work was being conducted as it had been contracted, the construction contract specified a formal reporting process, in which the RE checked the structures to see that they had been constructed to the contractually specified level of quality. This was either performed by the clerk of works, who continuously patrolled the site, or by the assistant section RE who would be called on site to examine the more complex or critical aspects of work. As each structure was completed, the graduate engineers would have to ensure that a form was signed by the assistant section RE, agreeing that the work had been performed to the appropriate standard. This form was copied, and sent to the RE, to the site main office for inclusion into the dayfile, and one copy was retained by the team.

Another formal accountability mechanism documenting activity on the site was the 'site record'. At the end of each day, these were filled in by the engineers (on a pro-forma sheet), collected together and filed, providing a common resource for the team to examine. Copies were also taken and passed to the main site office, where they were forwarded to the design co-ordinator and design engineer, the RE, and the other groups affected. The site record provided a means of 'covering the teams backs', so they could not be accused of failing to notice design-critical information.

Temporary works design meetings were held between the construction teams and the design engineer, and these were used to co-ordinate the design of the temporary works with the requirements of the team. Design meetings were also held on a two weekly basis alternating with the temporary works design meeting, to show the RE the preliminary drawings. Occasionally, these meetings would result in the RE demanding changes to the designs. Meetings with the environmental and railway ORGANISATIONS were also held on a monthly basis. The temporary works designs had to be 'passed' by them and they had the legal right to request change or even complete redesign of the temporary works drawings.

By exposing the roles of the agents involved in the functional system, and their responsibilities within it, it is possible to gain a better understanding of how the division of labour operated in the functional system on design tasks. Together with the phases in the cycle of design, the roles and responsibilities of the agents within the design system determine the pre-existing organisation of work; any design work that is carried out will have to be performed within this structure.

## 5.5 Transformational work in design

### 5.5.1 Inputs, outputs and transformational activity

Each phase of activity within the framework of the cycle of design was initially described in terms of its inputs and outputs. This approach was derived from the computational, information processing nature of distributed cognition, where functional systems take an input, and perform representational transformations on it to produce an output. By defining these inputs and outputs, the computation that was required to transform them could be clearly specified. Determining the inputs and outputs for each phase meant that it was possible to focus and structure data collection on the transformational activity within these phases, to examine how one was mapped onto the other. Once the phases had been defined (section 5.4.1), data collection involved looking through documents, interviewing people about their work, and observing the information that they gathered or were sent, and the information that they produced and gave to others. An example is given below of one phase (information gathering), to demonstrate the input and output representations from this phase:

**Inputs.** The information gathering phase of design was a continuous, ongoing process that involved searching out discrepancies between the construction programme (incorporating the schedule, permanent works and temporary works drawings) and the state of the site itself. Information relating to the state of the site was collected from the different groups of workers on the site, each using their different skills and experience to determine these discrepancies.

**Outputs.** The outputs of the information gathering phase were held informally in the heads of the engineers, foremen, gangers and labour as general information about the site. In addition, the graduate engineers would either record problems in a works record, or as in most cases, they would mention them to the site engineers. Other artefacts were used to represent problems, including notes and memoranda on desks and in files, and as the 'back of an envelope' sketches that the engineers took to represent spatial relationships between objects that were hard to describe in text. The paper based artefacts generated in this phase were often annotated with text and numbers over time.

This was done for each of the six phases. In some cases, a fuller understanding about the inputs and outputs of phases emerged through examining the transformational activities changing the inputs into outputs. The understanding of transformational activity and the input-outputs therefore evolved together, each providing clues to the composition of the other. This co-development of the organising structure and the data it embodies is a feature of the ethnographic method, and not a failure of it - emphasis is not placed on theory testing and validation; rather, it involves an agonistic process of reflection on the organisation of activity.

### 5.5.2 Computation and re-representation

Cognitive theory posits that information processing occurs through transformations on representations, turning inputs into outputs. Distributed cognition therefore examines transformational activity on external representations (the artefacts, or representational media) that processes inputs into outputs. Thus, in a distributed cognitive study of design, data collection focuses on how physical inputs relating to the design problem are transformed into a representation of that problem, and how subsequent transformations on the representation result in the eventual output of a final design.

In the example of ConsCo, data collection involved identification of the representational media involved in this transformational activity. This was performed through examining the traces left in the world, in the design documentation (e.g. the 'works records', dayfile and drawing amendments), through interviews with the design workers to see what they did when they received information, and through observational work of the ongoing activities performed by the design workers. Data was therefore collected on activities and artefacts where the temporary works design representation was transformed. The types of data transformation observed took three forms:

- The transformation of information from one medium of representation into another.
- Change to information within the medium of representation.
- Representation co-ordination, involving the synthesis of information across different representational media into a single medium.

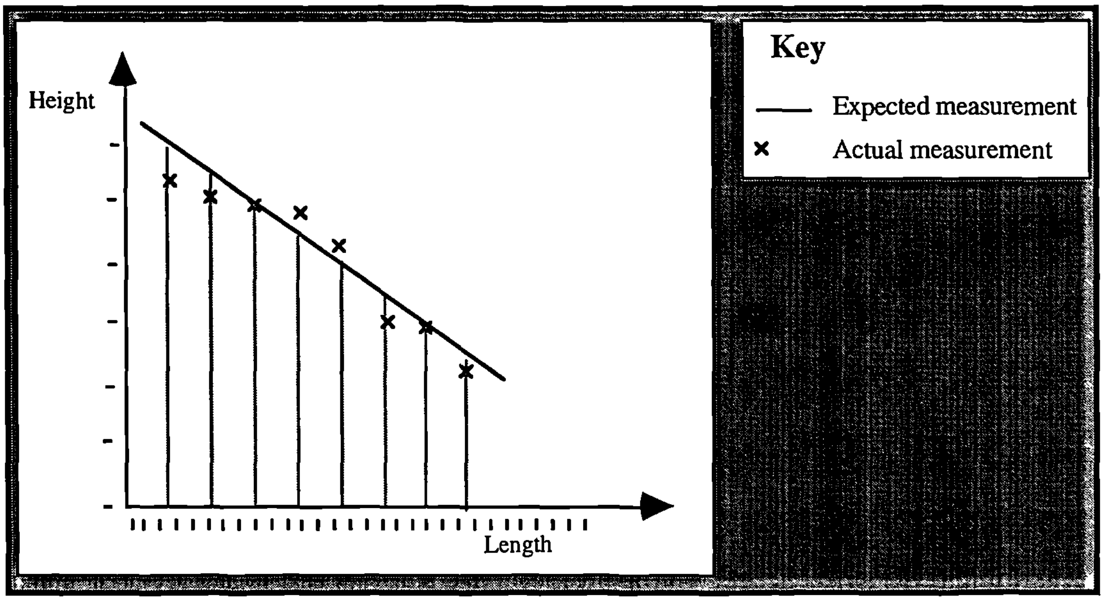
These are discussed below.

**Change to media**

In the example given, a transformation is made to the medium of the design representation, arising from the information gathering phase. This transformation formed only one component of the design process, and whilst it does not directly appear to be a 'design act' in itself, it does form an important part in a chain of representational transformations that together constitute design activity (see Appendix A). The example demonstrates how information represented in one rich medium is extracted and synthesised into a simpler representation with a structure that is appropriate for a particular task, that of comparing the designs to the constructions on site:

A graduate engineer had spent several minutes poring over a drawing taking measurements of the gradient of the surface of the bridge onto a hand drawn table. These measurements were then transferred onto a sketch, but in a different format to that of the original drawing: whilst the original drawing had been an overview of the deck (viewed from above), the sketch was a section through the structure (viewed from the side). In addition, the axes on the sketch were chosen so that they exaggerated the gradient and made deviations and discrepancies in the data more easily visible: the horizontal axis was on a scale of 1:250, whilst the vertical scale was 1:10. The sketch was then taken onto the site and real measurements taken with the geotechnical equipment were annotated onto it (see fig. 5.4.).

fig. 5.4. Sketch of road gradient.




The sketch clearly demonstrates that the measured slope had a gradient that did not match the gradient on the drawing. The form of this representation clearly demonstrated this, as the difference was exaggerated through the differential scales on the axes.

The reason for this discrepancy was that a sub-contractor had driven the piles to incorrect tolerances, the discovery of which had important consequences on subsequent building activities because it limited the loading that could be placed on them. This would necessitate a possible change to the construction process and the design of the temporary works used in it.

The graduate engineer left the sketch on the senior engineers desk, with a note attached to it explaining that he had found a discrepancy between the expected and actual gradient. The note further commented that he was going to be away from his desk for the rest of the day, but informed the senior engineers that he would be working at a particular location if further information was required.

It was common for sketches and tables to be generated from the drawings because the drawings were often too large to take on site and over-complex for particular tasks. These re-representations of information into *different* media therefore enabled more easily visualisable comparisons of data sets.

**Modification of media**

In this second example, a transformation is made *within* the medium of the design representation during the structural design phase. The example demonstrates how the status of represented information changed through simple modifications to its structure. The example relates to the temporary works design drawings, which were highly controlled and ensured that superseded or unfinished drawings were not used. This control was important to the design processes, because changes made to multiple copies of drawings were difficult to keep track of, and could potentially result in the construction of defective designs:

Temporary works drawings were created from the design brief by the temporary works designer. Various activities had to be performed to co-ordinate these designs: with the construction team, to see that the design matched their expectations; with the RE, to see whether the design was contractually valid; and with the other interest groups to see that it met their requirements. A final inspection then had to be made to check that the design was internally consistent and structurally sound.

Providing that changes were not required, at each of these stages, the design representation (the drawing) would be modified to demonstrate that a change to its status had taken place. This involved a stamp being used to show what the drawing could be used for. Red ink was used on these stamps so that unauthorised copying would not result in 'uncontrolled' drawings (because duplication resulted in black copies) which meant that it was possible to tell which drawings represented the current design.

The preliminary drawings and sketches derived from the 'design brief' were initialed by temporary works designer and stamped with the word 'preliminary'. When these drawings met the construction team's approval, they were stamped with the words 'for discussion'. The 'for discussion' drawings were then presented to the RE and the other groups involved. Each would sign the drawing when their approval was achieved. Following the approval of all of these groups, the drawing would be stamped with the words 'for inspection'. After a final check of the designs by an independent engineer, the drawings would be signed and stamped with 'for construction', whereupon they could be used in the construction process by the team as inputs into the *organisation of activities* phase.

Notably, the approval and stamping process did not involve the design representation being changed to another medium; rather it involved a change to the structure of the medium, each of these changes being used to determine what the representation could be used for, and what process should next be applied to it. Thus the design representation underwent a great deal of change, whist the medium carrying it was only slightly modified. However, the consequences of these small changes to the media were far reaching, and significantly changed the *meaning* of the representation.

**Bringing representations into co-ordination**

In order to process information from several sources, and in different formats, representations have to be *co-ordinated* with one another. For Hutchins (1988;1995a), this involved re-representing information from the ship's compass and visual position onto the navigational chart so that they could be combined into a representation of spatial location. In construction, this co-ordination occurred in a number of ways, using a wide range of representational media and co-ordination processes.

The nature of the co-ordination processes used in the example of ConsCo could be partially gleaned from the project documentation, in the project contract, the 'Contract Quality Plan' and 'Planning and Temporary Works Handbook'. However, the description of these representational mappings in the documentation was not clear. These documents only described when changes to representations had to occur, and what the end result should be. The most fruitful method of gathering data on co-ordination was observational, because many of these processes were managed 'on the fly' during activity. When followed up with informal interviews on these occurrences, it was possible to gain a better understanding of what the co-ordination activities entailed. An example from the fieldwork at ConsCo demonstrates an instance of such representational co-ordination.

In this example, the construction team's senior engineer was discussing a design problem with the temporary works design co-ordinator, as they attempted to develop a design brief for the temporary works design engineer (in the *generation of structural designs* phase). During this process, as they discussed the problem, they elaborated on old sketches, jotting notes onto them. They also referred to features of the drawings in speech by pointing at them:

Senior engineer (SE): 'If you look here, there's a barrel run there' <points at sketch generated in the meeting of a section view through a design structure>

Temporary works design co-ordinator (TWC): 'Yes I see'.

SE: 'So if we dig here...' <he holds one hand to the sketch and runs a finger on the other hand along a permanent works drawing (plan view) beside the sketch, indicating a line of reference>

TWC: 'No you can't do that because of drainage problems...' <pauses> '...No, no, I see now'.

SE: 'So if we cap these piles here...' <indicates several points on the sketch>

TWC: 'Yeah. OK. Lets do that'.

The discussion demonstrates how a common understanding of the problem was being negotiated by cross-referencing two different physical representational media. This occurred as the senior engineer mediated the co-ordination of two representations (on the different artefacts) by using his hands to demonstrate the relationship between the drawing and the sketch. He held one hand to a location on the sketch and the other, running along the permanent works drawing to indicate where the digging on the sketch (seen from the side) would have to be performed over the drawing (an aerial viewpoint). By co-ordinating these two representations in this way, information was created that could be used in developing a design brief for the temporary works design engineer.

### 5.5.3 Bi-directional movement of representations

The permanent works defined in the engineering designs for the construction site were largely pre-determined at the beginning of the project in the drawings generation by the Project Engineer, and in the tender application put forward by ConsCo. These contained the specifications on scheduling and building processes. However, not all of the details were pre-specified, and some design details were left to be determined at a later time.

Whilst the construction work stemmed *from* the drawings and work schedule, in reality, design and project planning were also performed by the team at many levels. These included suggestions for changes to the high level design concept in the materials and processes of temporary works erection, down to the implementation details that were left unspecified, and interpreted 'on the ground' by team members. In effect, whilst the flow of communication was planned as a one way channel from the Project Engineer, broken down into more manageable and simpler components towards the labour force and construction work itself, feedback about the site, in the form of various kinds of representation, also had to flow back *up* the chain of command, from the construction workers, to the team's engineers, and back to the Project Engineer, via the RE. Whilst movement of representations downwards towards the construction team was well specified by ConsCo's official procedures, the design related information circulating around the problems and conditions on the ground was less well specified.

Official procedures for the communication of information moving up the 'chain of command', from the implementors to the conceptual designers were arranged, involving meetings, but these were held relatively infrequently. Weekly internal team meetings were held, with other groups meeting on an even less regular basis (such as the design and team-RE meetings). In addition to meetings, paper based forms were used to communicate construction problems around ConsCo and other ORGANISATIONS, and engineers were obliged to fill in 'works records', which were distributed with the dayfile. Most of these 'upward' communications were, however, informal, brief and opportunistically passed on using the resources closest to hand, on post-it notes, in telephone calls, or as verbal messages. It was the nature of these opportunistic communications that they were easily lost or misinterpreted: informants said that they forgot verbal messages; written notes were lost under other papers or passed on too late to be of use. Such communications were also potentially ambiguous: the informants noted that (indexical) terms such as 'it' or 'that' could be interpreted differently by conversationalists. Whilst these messages were quick to create, their information could be misused, demonstrating the fine line between the benefits of formality and the costs of an increased bureaucracy (Dahlbom and Mathiassen, 1993). The next section therefore focuses on the co-ordination of representational transformations through communicative activity.

## 5.6 Collaborative work in design

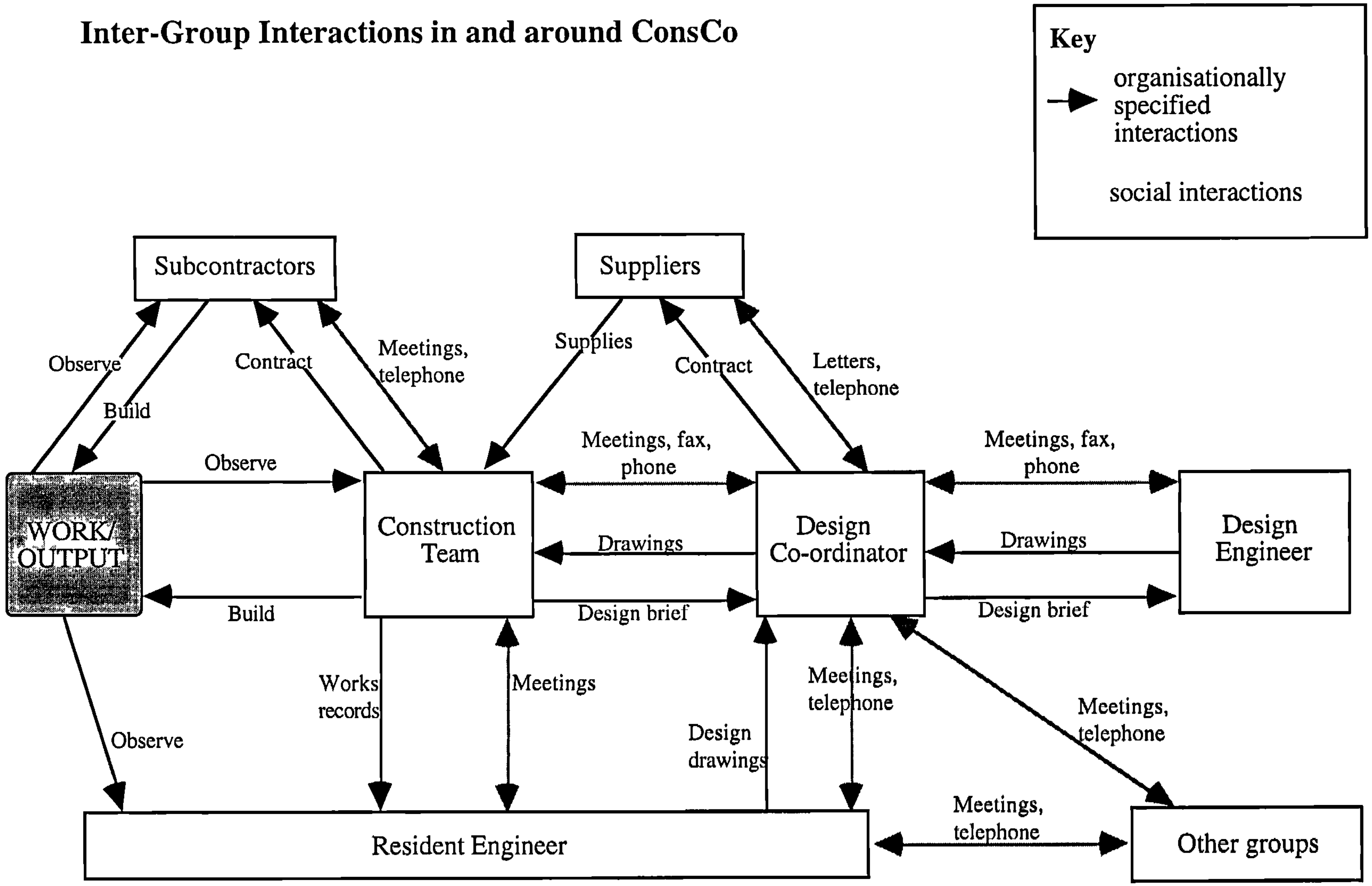
### 5.6.1 Communication and co-ordination

The maintenance of collaboration in engineering design was examined through the communication mechanisms that the design workers used to co-ordinate their work. These communications for co-ordination of the design process were initially prescribed by the organisation, which determined the responsibilities for particular activities. However, these communications were managed on an ongoing basis through the social interactions between individuals. Co-ordination occurred through communication between people, either directly, in speech or the transmission of artefacts, or indirectly, through actions on the world that could be observed by others and interpreted as having meaningful content.

Inter-ORGANISATIONAL activity in ConsCo was highly complex involving multiple people. This difference in the two forms of information, ORGANISATIONALLY structured, and those developed in an interactional, ongoing basis, is important in understanding how the design system processed information. ORGANISATIONALLY structured communication of design representations typically involved artefacts being transmitted to and from the site office, in various forms. This involved the transfer of design documents, using particular, pre-defined channels which specified who should make and receive the information contained within them. The permanent and temporary works drawings were particularly highly controlled to avoid the construction of out of date drawings, which would necessitate redesign of other parts of the project or even possible demolition of these structures. Whilst the official, formal process of design and construction activity was regulated, an informal, socially based design activity took place in parallel to the official account. These communication patterns are shown diagramatically in fig. 5.5.

Fig. 5.5

## Inter-Group Interactions in and around ConsCo



The socially based interactions formed a mediating activity, through which unregulated communication could take place. Informal channels of communication were important to the design process because the idealised ORGANISATIONAL procedures could be too inflexible to adapt to the complex and non-standard situations of the real world setting of the construction site. These socially mediated communications were hard to follow in the fieldwork because they did not usually persist in the environment for long as permanent physical records. They were typically involved in co-ordinating the use and creation of the ORGANISATIONALLY specified representations, and involved spontaneous social interactions and the use of opportunistic resources, such as pen and paper ('back of an envelope') sketches, scribbled notes on scraps of paper, or verbal queries yelled out across the office. The informal communications relied on artefacts existing in the environment and their use was therefore highly dependant on contextual factors.

### 5.6.2 Context and planning

The context in which the design activities took place was a major feature in communication, in determining the nature of the work, and the resources that could be applied to it. This was true for both designing the structures and the communication around the 'design' process.

The work of design was situated in an ORGANISATIONAL context, and various constraints operated on it; for example, whilst the construction team worked on weekends, few subcontractors or suppliers did. This meant that activities requiring the participation of these groups had to occur on weekdays, and tasks had to be allocated so that some types of work did not fall onto weekends. The range of activities that could be planned was therefore limited, and whilst there might be many theoretical ways that structures might be erected, in practice, these were reduced by practical circumstances.

Design was also situated in a physical environment, and the physical state of the site (including the weather, soil structure, positions and form of the existing structures) were a guiding feature on the possible ways that resources could be combined. The physical context of the site therefore provided constraints to the operations that could be performed and limited the possibilities for action by reducing the number of design options.

The physical context of the site also had a role in co-ordinating collaborative activity. Co-ordination of the information distributed between the participants was facilitated by the situated aspects of the construction activity, where the environment of the construction site and satellite office provided both resources and constraints to support collaboration. The actual processes used by the participants to co-ordinate their understandings about design problems on the site occurred through both direct and indirect communicative events. Direct communication involved activity that was primarily intended for communication (e.g. speech, letters and the dayfile), whilst indirect communication included activities that were not primarily communicative in their intent, although they had a secondary function as such. An example of such indirect communication in the construction team at ConsCo is shown below:

> The spatial context of the activity provided a mechanism for the transmission of information between people sharing that space. The organisation of the office was a major factor of how the construction team members interacted with one another, because it determined access to people and the artefacts used in the co-ordination of work activities. The physical structure of the 'open plan' satellite office allowed the behaviours of the construction team to be organised and to facilitate *ad hoc* communication, in a way that would not have always been possible under different environmental conditions. The engineers and quantity surveyors were therefore able to see when other people were present, to speak to them without having to move from their desks, to overhear them on the telephone or when speaking to each other, and to see the information laid out on other people's desks.
>
> The workplace was covered with paper and other sources of information. The walls of the office were covered in pinned up artefacts, including permanent and temporary works drawings, sketches, scheduling charts, calculations, photographs, calendars, information tables, the addresses of suppliers and subcontractors, and other information deemed relevant. When information was required from a person who was not physically present, this material on people's desks and wall ('desk litter') could provide clues to their location, in the forms of the drawings and other documents on the desk, as well as the task that they were currently engaged in. Other artefacts also provided information about the whereabouts of people: if a person's Wellington boots and hard hat were missing, they were probably out on site; if someone had a pair of muddy boots under their desk, it meant that they had been on the site and could be asked about the current work situation. Even the window was used to see whether people's cars were in the car park outside the office: if this was the case, then that person was likely to be on site.

In the example above, the physical context provided resources for explicit communications to be interpreted more easily than in a less well resourced setting. Spoken communication was conducted from the desks, allowing all of the participants in the room to be aware of developments, or allowing them to contribute to the discussion. When the senior or site engineers wanted to speak to the graduate engineers, they would stand up and chat over the tops of the partitions, providing a visual and auditory focus of attention in the room. This allowed people to work whilst keeping an ear to the conversation, keeping abreast of developments, to ask questions, and to add to the discussion. In addition to these 'open' conversations, telephone conversations were carried out in loud voices; this was partly because the level of ambient noise in the room could be fairly high, but also because it allowed the others in the room to overhear (one side of) the conversation. One of the site engineers in particular would deliberately raise his voice whenever he was speaking about topics that he perceived to be particularly pertinent to the others, even standing up and waving his arms around to gain attention, or pointing to artefacts that were relevant to the discussion so that the others in the room might get an idea of the topic of conversation.

The physical nature of settings can also have a major impact on the patterns of communication used by designers. In the construction team at ConsCo, the size of the site was a defining factor on the communication that was possible:

> Whilst the participants in the information collation phase were centred in the satellite office, they spent large amounts of their time on site. Visits onto the site provided an opportunity for the engineers to engage in *ad hoc* encounters with the workers on the site which provided a source of information on any problems developing on the site. However, the distributed nature of the site made contacting individuals difficult. When people were not present to talk to directly, other media were used to communicate, either through the use of the radio link, through placing written notes, sketches, method statements or risk assessments on people's desks, or jotting notes onto a whiteboard. Messages were also left with people who were in the office for when that person came back.
>
> Contact between the dispersed team members with the site which was some distance from the satellite office was made possible through the use of a portable hand-held radio link, which allowed the engineers and gangers or foremen to communicate with each other (eight radios were shared by the team). These radios were kept on all of the time so that contact calls could be made. The background noise of the radios was also used as a means of indirectly monitoring general activity on the site. The almost constant babble of the radios in the office meant that distant conversations could be attended to.

The use of radio in communication is an interesting feature in the co-ordination of the construction team, because of the qualities of the medium. Radios, unlike the telephone, are set to an open channel, and communication therefore takes place on a common wavelength. In the field study, this meant that both sides of communications could be overheard by non-participants who had access to a radio. As with an open plan office, which allows overhearing, or 'surreptitious monitoring' of conversations, the radios used on the site had a similar function for spatially distributed individuals. This demonstrates how a communications technology can enhance task performance when it conforms with, and meets the requirements of work practice.

### 5.6.3 The allocation of tasks

The division of labour is a central aspect of distributed cognition and the mechanisms that are used to allocate tasks need to be made explicit to show the computational structure of the functional system. In the example of ConsCo, tasks were allocated to people through a number of means, depending on the ORGANISATIONAL structure of the functional system and the contextually dependant features of the setting. Communication was used to co-ordinate the allocation of work over the individuals involved in the design process, and studies of communication within the functional system provide an example of how the division of labour was organised, both as an ORGANISATIONALLY determined and emergent phenomena.

Whilst allowing a degree of autonomous freedom in behaviour, ConsCo operated within a central ORGANISATIONAL framework that allowed the participants an understanding of the responsibilities and roles that each was expected to perform. Knowledge about how to operate within this framework was distributed across the Contract Quality Plan, the experience of the participants, and in the structure of the artefacts used in the construction process, and these were often interweaved together. An example of this knowledge distribution occurred when a graduate engineer was asked to check on the particular characteristics of a concrete mould (known as "shuttering") by the clerk of works:

> According to the Contract Quality Plan, queries raised by the RE or their staff should involve recording the problem, finding the answer, and filling out a 'works record', which would be sent to the site office, placed in the dayfile, and a copy sent on to the RE.
>
> Accordingly, the graduate engineer filled out a works record form with the problem request and sketched a diagram of the concrete shuttering and the setting it was placed in. He telephoned <someone> off-site, and discovered that the information he needed about using the shuttering was in an advertising/promotional leaflet sent out by the shuttering company, and was held on file in the team office.
>
> The information was lying on one of the foremen's desks, who had been looking through it with an eye to ordering more materials. The engineer read off the technical details from a table on the leaflet and added this information to the form.
>
> The engineer then posted the works record to the site office for inclusion into the dayfile for circulation. As a works record, no accompanying information was required because the form of the document meant that it would always be processed in the same way. Due to the slow speed of the internal postal service, the engineer later went back on site, located the clerk of works and reported his findings personally.

In this case, knowledge distribution occurred over the participants involved (graduate engineer, unknown telephone informer, foreman, clerk of works, and RE), and artefacts (the work record, dayfile, sketch, leaflet). This involved the use of different channels of communication (spoken, postal, and telephoned), each with different qualities for the transmission of the information. The form of the medium was utilised to determine how the information represented was to be applied. Whilst the ORGANISATIONAL structure determined who had responsibility for various features of work, the work itself was performed through social mechanisms. In this way, the ORGANISATIONAL structure functioned as an (incomplete) resource for determining the allocation of work, rather than an absolute rule set, and it was loosely applied as a resource in the performance of work. It did not determine the physical actions required, which were selected according to a range of other factors (social, material and spatial).

The organisation of activities in ConsCo was loosely knit, relying on a 'just in time' management ethos; in reality, informants said that this translated into a fire-fighting mentality, where design information was often described as being delivered 'just too late', leading to delays in the project. Long range forward planning was not always possible because it was often difficult to identify problems in advance, and because team members had little time with which to generate detailed activity plans. Most of the observed activities were arranged 'on the fly', emphasising the contingent nature of collaborative planning, and the *ad hoc* methods used to achieve this co-ordination. An example of one such planning situation observed is given below:

<Scene: A site engineer is on the telephone, speaking to a remote person and discussing a concrete pour. Only this part of the telephone conversation could be monitored by the fieldworker>

Site engineer: <stands up and speaks loudly into telephone> 'So, what I'm asking is: should we put concrete into the tower?' <raises his head and looks at the senior engineer with raised eyebrows>

Senior engineer: 'Yes'.

<Site engineer, completes the telephone call, then lifts a radio to speak to a foreman to give the go ahead. A graduate engineer overhears this:>

Graduate engineer: <orients towards senior engineer> 'Do you have any spare...<pause>...can I have three cubic metres?'.

Senior engineer: <Pauses. Looks at ceiling. Pushes tongue into side of mouth. Pauses. Looks at graduate engineer> 'OK. Yeah.'

<Site engineer overhears this and radios through to the foreman to arrange it>.

In this observation, the potential to overhear telephone conversations (because of the open plan office space) is used by the site engineer as a means of asking the senior engineer if he can go ahead with construction. This was not pre-planned, but arose from a request for information arising from a distant third party. A graduate engineer, in turn, overhears this, and makes a request for materials, which was arranged by the site engineer. None of this was prepared in advance, and the tasks were fluidly discussed and finalised as the participants were made aware of on-going activities around them, which they used to initiate and direct their own work.

## 5.7 Summary

This chapter demonstrates how field data about the construction design process was collected. It describes how the processes observed were co-ordinated, and how the work of design was performed within one construction project. The principles that were used to structure the collection of field data draw from distributed cognition in describing the task of the functional unit by specifying its goals, the resources that the system has to operate upon the problem, and the relationships between the members of the functional system. The structures used by the participants in organising the design process are then described through the activities that the functional system performed, and the roles and responsibilities that the agents played in performing these activities. The transformational work that was involved in problem solving was then discussed, using examples to describe how the functional system achieved its computational goals. The communication structures that were used to co-ordinate these transformations were then described, showing how context was a vitally important factor in co-ordinating the division of labour across the elements of the functional system.

The design process was described as involving a cycle, incorporating data collection (an ongoing process), framing of the problem (through creating a set of specifications), solving the problem (in abstract terms), organising a means of activating the (abstract) solution, then implementing the design in a physical construction. Much of the work appeared to involve the setting of specifications and unearthing of constraints to discover the boundaries of the design space. The final phase of design involved reporting on the outcome of the implementation (success or failure in matching the designed solution to the design problem, within the specifications and constraints), which would be utilised in the next cycle of design as an input into the information gathering phase.

Whilst one person (the design engineer) was involved physically transforming the temporary works problem into a design solution, the specification and determination of constraints on the design itself was highly collaborative. Work was distributed over the collaborating designers through a variety of means by which the task was decomposed. The technical work performed by the engineering designers at both of the projects studied (see also Appendix B) involved similar patterns of activities.

Both studies demonstrate how the physical environment and social organisation are major determinants of the actions performed in design. A central feature of design involved the use of artefacts of many kinds, in the use of drawings, but also other artefacts that represented non-spatial and more transitory forms of information.

The design artefacts were generated by re-representing information from the site, or from other artefacts themselves generated elsewhere in the design process. They included a number of different representational forms, including text and speech as well as diagrammatic and tabular forms. Maintaining control over the processes of engineering design was an integral part of the engineering design process observed in the fieldwork. Control of the design artefacts was deemed to be of critical importance in this management of the design process. Only controlled representations were allowed an 'official' status in design work, although in practice the design workers predominantly used unregulated representations in their day-to-day work activities.

The data collected in the fieldwork is examined in more detail in the next chapter which applies distributed cognition as an analytic tool to expose the *underlying* mechanisms of co-ordination in design. It draws from the field studies to provide a distributed cognitive account of collaborative engineering design in construction.

# Chapter 6

# Synthesis - Distributed Cognition, Design and the Development of Technology

*'Almost certainly, the engineer is part of a team, and its collaborative processes contribute to the picture... the functioning cognitive unit is the team, plus its physical support system of scratch pads, technical tables, computer-aided design systems, and so on'. (Perkins, 1993, p94).*

## 6.1 Overview

This chapter applies the framework of distributed cognition to build a 'domain theory' about engineering design in construction, showing how engineering design work is organised within its context of action. The domain theory itself is separate from the framework of distributed cognition and the fieldwork, and describes the intrinsic characteristics of work within a particular domain, although it is systematically linked to them through application of the analytic theory and data collection.

The field studies summarised in the last chapter are largely descriptive, and although guided by the requirements of the distributed cognitive analysis, they do not examine the underlying mechanisms through which the design work observed was co-ordinated. This chapter draws out the mechanisms behind the activities, and examines the structure of collaborative engineering activity. This deeper level of analysis provides a description of the functional system in terms of its cognitive properties. The consequences of the analysis for systems design are followed up with suggestions for systems design.

The chapter falls into three sections:

i. A general examination of collaborative design work, looking at the forms of communication used and the resources available. The section focuses on *what* was done in the design process.

ii. The activities of design are linked and examined through the framework of distributed cognition. The section describes *how* the work was co-ordinated, both as a deliberately managed and emergent phenomena.

iii. The analysis of collaborative design is used to generate implications for the specification of technologies to support the underlying mechanisms of co-ordination between designers, and across the environment that design occurs within.

## 6.2 Activities involved in engineering design

### 6.2.1 Design through and around artefacts

The fieldwork demonstrates how the construction team stripped detail from the artefacts they used as well as adding knowledge to them. This created more succinct and modified representations that were better suited to their localised purposes. As representations were modified, their underlying informational content underwent change, and information processing occurred. At the end of a long chain of such transformations, the design representation had progressed from a definition of the problem into a solution for it.

A huge range of artefacts were used in the design processes, some of which were not involved in collaborative activity, others which were co-opted for collaborative use, and yet others which existed solely for the purpose of communication. These representational artefacts ranged from basic pen and paper sketches, through detailed drawings and contractual documents, to the use of sophisticated CAD technology to maintain complex, multi-layered design models (Appendix B). Whilst some artefacts represented the form of the design, other artefacts were used to convey information about the current state of the design process between the designers. These took the form of specification documents, schedules and other artefacts that represented different forms of knowledge *about* the design. In addition, the design artefacts such as the drawings and the CAD models were not solely created for the benefit of individual users, but could also be used as a means of transmitting often elaborate and easily misunderstood information between individuals with different perspectives and understandings about the design.

The designers themselves described the drawings as 'objects of work' rather than as transitory media for communicating design concepts with. However, drawings were an important medium that allowed a task to be distributed over a number of actors. In some cases they were the sole means of communication between the drawing's creator and the user of that information (as with the permanent works drawings between the Project Engineer and the construction team). In other cases, drawings were used explicitly as a medium for communication - for example, the 'for comment' versions of drawings, used as a mechanism for ironing out contradictory understandings. Stamps and signatured initials added meaning to the drawings, determining their status in the design process (section 5.5.2) by adding procedural information to the spatial representation. Annotations on the drawings added another dimension to communication, conferring a spatially sensitive quality to design communication, because the annotations could be seen in conjunction with the graphical features they referred to.

Sketches were used as a means of communicating in a similar way to the drawings, but they were more explicitly used for communication, either handed, faxed or posted between co-workers. The paper size (small: A3-A5) and rough pencil markings used in the sketches demonstrated that these were transitory media and were not intended as fully comprehensive design representations (as the drawings were). These qualities of the artefact provided a clue to the reader that they were meant to be interpreted differently to drawings. Sketches were therefore used as ongoing interactional props, rather than as completed achievements. Other representational media were used in the design process, some based on formal procedures, such as schedules of events, letters, forms and meeting agendas (and available in the dayfile), and others, such as notes and memoranda that were created and used 'on the fly', but not commonly available (section 5.6.3). In most cases, text based artefacts were used for the non-spatial aspects of communication in design activity, such as the allocation of responsibilities and resources, and in generating a shared awareness of past, current and future activities undertaken.

Three central features of how the artefacts observed were used in design are described below:

- There was common access to most artefacts in the workplace: they were pinned to walls, loosely racked up in the offices. In some cases, comments on them were forwarded to the document control archive and accessible on request.
- Work on drawings and sketches allowed the externalisation of an individual's internal cognitive processes so that they were available to the other group members (Perry and Thomas, 1995). By working on plans, individuals could express their ideas into the world, where they were open to discussion and development within a social setting. Thus, the creation of external representations opened up internal cognition and the rationale behind individual actions and plans to the other people that these plans and activities affected.
- The ORGANISATIONAL structure determining the relationships between members of the functional system established the access to, and permission to modify, certain representations. This meant that these were propagated to the people who required them, and not made available to those who were thought not to need

them. This filtering of information helped to prevent 'information overloading' and increased the informational relevance of communications that did take place.

### 6.2.2 Mechanisms of co-ordination

In both sets of fieldwork (Appendices A and B), a large number of people were involved in the design process, each engaged in different, but highly interrelated aspects of work. Design work crossed ORGANISATIONAL boundaries and involved multiple individuals, across all strata of the ORGANISATIONS involved. To co-ordinate their work activities and to manage the distribution of labour, individuals had to organise their own activities to pass on relevant information that they had collected, created, or modified. In practice, the fieldwork has shown that the mechanisms used to co-ordinate activity appeared to fall into two main dimensions: ORGANISATIONALLY mediated, explicitly recognised mechanisms, and socially mediated, implicit mechanisms. These are elaborated on in more detail below.

**ORGANISATIONAL procedures**

The procedural mechanisms of co-ordination were dependant on the internal structure of the ORGANISATIONS, and in the relationships specified within legally binding contracts. These mechanisms pre-determined the structure of the interpersonal and inter-ORGANISATIONAL relationships, the roles they played, and the resources that were to be applied under particular circumstances.

The pre-specified 'official' organisation of activity was most explicitly applied to the management of drawings and related correspondence in the 'official' descriptions of management for the design process. The procedurally based mechanisms of design co-ordination were also evident in interactions between ORGANISATIONS, in the communication of meeting agendas, drawings, contract related material, and specifications. Within ORGANISATIONS, there was a lower level of procedural co-ordinating activity, although examples were observed in ConsCo (between the construction team, the design co-ordinator and the design engineer, using the design brief) and (see Appendix B) in the BEG (between the structures and M&E team, in producing 'co-ordination drawings'). Between members of the same co-located teams, almost no predetermined structure to the design process was observed, and collaborative activity was maintained almost entirely through social mechanisms. Seniority was the only ORGANISATIONALLY determined feature that was observed within teams, determining responsibilities for actions undertaken.

The ORGANISATIONAL mechanisms determining the procedures applied to the design process were occasionally subverted, for example where unregistered sketches and informal 'chats' were used to clarify aspects of the design. Unofficial mechanisms for communication and co-ordination were used because the official documentation did not always capture all of the relevant information about the design. For example, the documentation could only be interpreted with the assistance of the creator, as observed in the BEG, with the architect's drawings of the Roman's House Project (Appendix B). In practice, the 'officially' approved mechanisms of document control only appeared to be applied rigorously at significant transitions in the design process, where decisions taken could deliteriously affect subsequent developments.

**Social practices**

The informal communicative mechanisms used to co-ordinate the collaborative activities of the designers involved a number of different activities dependant on the particular circumstances: the nature of the design problem, the time available, the spatial locations of the designers and the local resources available. These mechanisms for co-ordination fell into three main categories:

• **Speech based.** One of the main means of co-ordinating the design workers was through meetings, including meetings that were explicitly arranged between people when required, and chance encounters between people in the workplace. Arranged meetings were used to discuss poorly understood areas of design (ill-structured problems), whilst *ad hoc* meetings and encounters were more often used as a means of clarifying minor, but commonly understood details of the design (well-structured problems, Simon, 1973). Another frequently used speech based method involved use of the telephone or radio, when the participants were in distant locations, and face-to-face meetings were difficult to organise at short notice. They were also used when arranging another form of co-ordination activity, such as a meeting, or drawing transfer. These technologically mediated communications tended to be brief, relative to face-to-face conversations.

• **Text and Artefact based.** Sketches were used, often initially in solitary work, but were seconded as an aid to communicating ideas about spatial relationships, both in face-to-face meetings (for example, the representational co-ordination described in section 5.5.2), or less interactively, when faxed between people. Notes and memos were used as a means of asynchronous communication between design workers when the recipient to the communication was not physically present (as in the gradient example of in section 5.5.2). Email, when used (Appendix B), performed an equivalent function to paper-based notes, with the advantage that a single message could be delivered to multiple recipients, acting as a personalised bulletin board.

• **Context based.** Designers made use of the actions of the other people present in the same location, and on traces of their activity in the environment (perceptual monitoring) Good examples of this can be seen in section 5.6.2 on indirect communication, where 'desk litter' or mud on boots was used to provide information on a person's location. This was possible because of commonly accessible information in the world, such as the physical material on desks and walls, and through overhearing conversations in a shared space. An understanding of these communications was possible because of the design workers common background knowledge from their shared previous experience or similar training.

**Artefacts supporting co-ordination**

The artefacts used in design activity fell into two types, one supporting and moderated by ORGANISATIONAL procedures, the other, by social processes. These are described by Perry and Sanderson (1997) as 'design' artefacts and 'procedural' artefacts. The artefacts supporting the ORGANISATIONAL procedures included media such as the drawings and the dayfile, which were structured according to established in-house procedures (e.g. Contract Quality Plan), as well as standard engineering and commercial practices. Artefacts supporting the social processes of the design were not controlled by the standardised procedures, and involved media such as post-it notes and the jointly created sketches generated in *ad hoc* meetings.

The artefacts that supported these two mechanisms of co-ordination have been grouped into two forms, primary and mediating artefacts.

**Primary Artefacts** - These artefacts carried the representations of the 'officially approved' design and their use was carefully regulated by the ORGANISATION. They formed the basis of the ORGANISATIONALLY structured design work, and included the project drawings, controlled sketches, controlled letters (in the dayfile), risk assessments, calculations, and other design specifications (e.g. the design brief).

**Mediating Artefacts** - These artefacts moderated the 'flow' of the design process, allowing the design representations to propagate seamlessly across the design system, co-ordinating the representational transformations on the primary artefacts. Examples of mediating artefacts included rough sketches, minutes of meetings, post-it notes, diagrams, faxes, informal letters, annotations on drawings, and mentally held and verbally encoded information. Mediating representational forms provided the means of organising the participants around the primary artefacts, and were used in a relatively unstructured fashion by the actors observed. However, the ORGANISATIONS observed had tried to make these more explicit by requesting that all paper records be placed in the dayfile.

Essentially, the primary artefacts were those that eventually fed into the final design artefact, whilst mediating artefacts supported the creation, manipulation and movement of the primary artefacts. The social interactions supported the more rigid, procedural structuring of work practice; each played a part in structuring collaborative activity and the interactions between them were crucial in examining the performance of design work. Below is a table of the differences between primary and mediating artefacts (Table 6.1.):

Table 6.1. A comparison of primary and mediating artefacts

| | Artefact Type | |
|---|---|---|
| **Features** | **Primary** | **Mediating** |
| *Organisational Status* | Procedural | Informal |
| *Maintenance* | ORGANISATIONAL | Social |
| *Informational Access* | 'Controlled' | 'Uncontrolled' |
| *Style of Use* | Rigid | Flexible |
| *Transience* | Permanent | Impermanent |
| *Descriptive Quality* | High | 'Fuzzy'/Low |
| *Representational Encoding* | Structured | Unstructured |

It is however, important to recognise that primary and mediating artefacts could both exist on the same medium. An example of this occurred when textual annotations (mediating artefacts) were written onto drawings (primary artefacts).

### 6.2.3 Synopsis of engineering design activities

In both of the field studies of engineering design, similarities and differences were observed in the activities performed. However, the differences in patterns of activity appeared to derive largely from the different design problems and the local resources available. Despite these differences, a number of similarities in design activity were observed.

The fieldwork demonstrates how the actors in the workplace achieved design solutions, demarcated problems, and discovered the resources and constraints on action. It shows how they determined the goal states, and mapped from the current state towards the goal state through the use of various representational artefacts and processes. A central feature of the design activities observed was that much of the work involved in design was in maintaining the co-ordination of distributed activities as the collaborating actors attempted to work together to produce a single design solution.

The behaviour of the designers was constrained by their organisation with respect to one another, which determined the *processes* of design work. Many of the artefacts within the design process were managed in systems which controlled access to the design artefacts. However, alongside this structured process of design management, informal communication processes were used to co-ordinate the activities of the participants and in the transmission of representations between the designers. These informal processes were mediated through locally determined social interactions. Whilst the artefacts produced by these *ad hoc* activities were often short lived, ambiguous or contradictory, they were highly flexible. This allowed many of the difficulties encountered in the ORGANISATIONAL procedures (such as system rigidity, system incompleteness and time constraints) to be handled quickly and simply, without recourse to the restrictive demands of the quality control systems.

A central feature of the study was the observation that design work was not wholly performed by those labelled as 'designers', but also include other stakeholders involved 'downstream' in setting the problem requirements (Perry & Condon, 1997). Many different individuals and stakeholder groups contributed to the final designs, ranging from the client to the planning authorities, and even the construction workers themselves. Through generating and processing representations of the design, they moderated the process of design itself, even if they were not engaged in managing or bringing together these interdependent features into a design solution.

The other important factor observed in design activity was the role of context: design is an ecological process. Historically, design has been generally considered to be performed mentally (section 2.2.1), rather than as demonstrated in the fieldwork, where the *context* of the activity had a strong influence on the activities that were performed. The effects of context on the process occurred both as physical constraints on the possible design solutions, but also through determining the media of communication between the collaborating designers. The media used in communication was an important factor in determining the design solution, because it determined how the representation was carried, and how it could be transformed.

The fieldwork has described the activities of designers in real problem situations. This can now be examined within the framework of distributed cognition to demonstrate how the internal structure of the functional system co-ordinated their distributed actions to generate a design solution. This analysis can then be used to identify areas where technology may be applied to assist collaborative design by providing additional resources for, and supporting the division of labour between design workers.

## 6.3 A distributed cognition of engineering design

### 6.3.1 Communication, co-ordination and collaboration

Examining the communication methods used between the designers can give an insight into the co-ordination of their activities. Distributed cognition is used here as an analytic tool to develop a more abstract understanding of collaborative engineering design. This will demonstrate how the relationships between co-workers were mediated by the transmission of representations in communication. These communications were established through various forms of representational media.

In the field studies, one of the commonest forms of communication observed between the designers was through spoken language. Speech formed a 'high bandwidth' channel for bringing the mentally held representational structures of the different actors into co-ordination with each other This allowed them to produce an intersubjectively, or commonly understood, state of affairs that could then be negotiated. However, in some circumstances, language failed as a form of co-ordinating activity, because of its potential for ambiguous use, its need for the synchronous presence of all parties, and lack of an enduring physical record. Other methods of communication, using media with different properties were therefore chosen by agents in circumstances where language proved to be inadequate. The form of media chosen to co-ordinate representations was therefore dependant on the *context* of that interaction.

The function of communication was that of co-ordination, so that labour was distributed around the functional system for the solution of the design problem. Hutchins asserts that this is where human cognition is so advanced; it 'lies in our ability to flexibly construct functional systems that accomplish our goals by bringing bits of structure [i.e. representational media] into coordination' (1995a, p.316). This co-ordination allowed work to be broken down into sub-tasks within the capabilities of the individuals in the design system. At an abstract level of analysis, these communicative events were used to bring the design representations (including mentally held information, the drawings, schedule, specifications, sketches, and other documents) into co-ordination with one another. As design representations were communicated (or propagated) across media, information processing activity was performed on them.

### 6.3.2 Distributed computation and collaboration

Changes to the state of an artefact can transform the represented material within that artefact. Whilst simple re-representations could result in changes to the original information, many trivial changes could snowball to cause complex information processing activity. The computation is performed by structuring the division of labour in the functional system so that the representations involved in the activity can be brought into co-ordination with one another.

The analysis of multi-participant design has many similarities to that of navigation (see section 4.3.1): a range of artefacts were used, through which design representations were propagated and re-represented (either in different media or through being imbued with different properties), until they matched the problem situation to the goal situation. Thus, in ConsCo, the design brief was transformed into a temporary works drawing, and in the building engineering group (Appendix B), architectural drawings were transformed into both structural drawings and detailed mechanical and electrical specifications.

The transformation of problem situation into design solution therefore involves a computation. In the field studies this was implemented within a distributed cognitive architecture, incorporating a number of agents with different skills and roles, in combination with a range of other artificial (in the sense of Simon's [1981] definition) representational media, operating in an environment rich in resources to structure these transformations. Social and ORGANISATIONAL protocols were used in combination with the internal structure of the technological artefacts used, in concert with the resources and constraints of the setting, which came together to determine the outcome of these computations. Communicative acts were not distinct from the computations involved in information processing the design work. The computational and social processes were intertwined together so that tasks could not be broken down into an abstractly described problems without reference to their implementation. This description of design is a radical departure from the current understandings of design described in section 2.2, which have tended to focus on the abstract design space and unsupported cognitive activity in design.

In the two field studies documented, there were many possible methods of bringing the representations into co-ordination with one another to fulfil the requirements of the particular design task and to compute solutions to design problems. The design settings observed were rich in artefactual resources that could be used by the functional systems to structure their activities. In a given situation, one of several possible combinations of mediating structures (i.e. the representations used in intermediate stages of the computation) will be chosen in determining the architecture of the computational implementation. Exactly how competing resources and computational systems are selected is not yet understood. This is an important research question, but lies outside the scope of the thesis.

### 6.3.3 The structure of informational resources

The fieldwork demonstrates that artefacts were used as devices for passing information (as representations) around the functional systems of design. These artefacts provided the media through which the design process was distributed, allowing the representations to be passed across social space.

The computational architecture of the design systems arose through the relationships of agents, to one another, to the task, and to the artefacts that they used. The resources that agents used to structure their activities are broken down below. These include structure from the state of the world, from the other people involved in the task, and from within the personal cognitive worlds of individuals:

• **State of the world:** In the work systems observed, this appeared to be a critical resource for action. The state of the world determined access to physical resources. Activities were made explicit by mechanisms that included open plan offices, current drawings laid out in racks, and access to the dayfile for current correspondence. This structure allowed particular forms of co-ordination, so that agents could speak loudly when they believed that other people might need to hear part of a conversation, or where current work on desk surfaces could be seen and acted on if necessary by others.

• **Other people:** Other people were able to structure an agent's work by providing instructions on how tasks were to be performed, and in providing reminders for actions to be performed. Reminders were enacted either through direct interjection, or through the 'pipelining' of work. Pipelining activities occur through the serial performance of work, where an artefact is passed between agents, where the artefact contains clues to its use through its internal structure. Pipelining was observed in the sketch passed to the senior engineer by the graduate engineer representing the mismatch between designed and actual gradients (section 5.5.2): this artefact acted as a reminder to the senior engineer that he would have to contact the resident engineer.

• **Within individuals:** The structuring of mentally held informational resources was not directly observable in the fieldwork, and lies outside the scope of this thesis. Naturalistic research cannot reveal mental processes other than through the 'traces' that they leave in the world. Whilst these mental constructs were not explored, they were nevertheless understood to be an important resource for co-ordinating work.

### 6.3.4 The division of labour

In a distributed problem solving system, there may be many ways to organise groups of agents to distribute the computational load amongst them, some of which may be better than others (in terms of their speed, processing resources required and proneness to error). The division of labour determines the computational architecture of the problem solving unit, because it establishes the resources and processes that can be brought to bear on the problem representations.

The standard operating procedures (SOP) of work in construction engineering, which in ConsCo included the Contract Quality Plan and Planning and Temporary Works Handbook, were used to organise the allocation of work to individuals, specifying how they were to interact with one another. These procedures determined how resources were to be used in a similar way to the 'Watch Standing Procedures' in navigation. However, unlike in Hutchins' cognitive ethnography of navigation, social and situational factors played a far more central and 'contingent' role in defining how engineering design work was conducted in construction. In construction design, the SOP was complemented with an informal system of social mediation and was even subverted on occasions when it became excessively cumbersome. This social element to the computational system incorporates elements of engineering and construction practice as learnt by the actors ('cultural' knowledge), the generation of knowledge through interactions between individuals (socially constructed knowledge), and situated determinants that limit activities through constraints on the resources available, such as materials, time and money (this is situated knowledge [Lave, 1988], or 'knowledge in the world' [Norman, 1988]).

In the functional systems observed in the fieldwork, work was allocated between actors through two main mechanisms. The most commonly described of these involved a pre-determined, systematic division of labour, as observed in the SOP procedures:

**systematic division of labour:** The SOPs were pre-designed by managers to optimise and control work processes, and so do not allow local adaptations to the contingent nature of the situation[1]. In general, such pre-designed ORGANISATIONAL systems for breaking down work are the preferred method for performing work. This is because the method allows the component parts of tasks to be manipulated in advance, and should theoretically provide the 'optimal' allocation of processing resources for the solution of a problem (Hutchins, 1995a). Pre-designed systems allow the decomposition of a task so that the computational load falls onto those agents with the best resources (skills and aptitude), and work is evenly distributed over the participants.

However, for activities that cannot be pre-planned by such systematic means, non-optimal, locally adapted, systems must be adopted, where the computational processing resources are not necessarily allocated to take best advantage of the available resources. Such a locally determined division of labour occurs through the ongoing division of labour:

**Ongoing division of labour**: The members of the functional system place constraints on one another by providing each other with partial computational products (the forms of representation in use at that phase of design, for example, drawings, partially completed drawings, memoranda and verbally encoded information). This was seen in pipelining behaviour. When there is no pre-specified, or previously negotiated division of labour, the interactants do the work that they are able to (or willing to do),

[1] The SOP systems did, however, develop through *indirect* adaptations to situations as they were refined and developed over time.

leaving the other members of the functional unit to complete the rest of the task. The functional system therefore adapts itself to perform work that has not been completed.

The ongoing division of labour involves 'supervisory reflection' (Hutchins, ibid.), as opposed to the systematic (SOP) model of activity, where optimal solutions to the divisional of labour are identified. However, a sacrifice must be made for each of the methods chosen, as optimality of outcome is matched against system dynamism. With the systematic approach, 'rules' must be well defined and fully comprehensive for every possible eventuality. These can make system behaviour slow and laborious, as the rule must be identified before work can be allocated. With the local adaptations, system control is not performed through an executive, and a system of distributed control can arise, evolving through interactions between people in locally negotiated agreements. This can potentially result in poor allocations of computational resources, and may result in incorrect outcomes, as non-standard computational strategies are applied.

### 6.3.5 The role of context in organising behaviour

A crucial understanding about human activity is that it occurs within, and is bounded by its context. Context determines the resources that are available for agents to operate upon. This was observed in the fieldwork, where the construction workers were limited to the resources in their offices and the site (section 5.6.2). The significance of context appears to be particularly important where cognitive activity is externalised into the world in cognitive artefacts, because access to these artefacts determines the cognitive, or information processing operations that can be performed. In a domain such as engineering design, cognitive behaviour cannot be seen as an abstract activity - it is dependant on a huge number of distributed resources.

The behaviour of design teams engaged in tasks involves a search for an ORGANISATIONAL and social structure that can be used to distribute the task so that the functional system can perform an appropriate problem solving computation. It is likely (although this was not directly observed) that many such structures may be explored, both successfully and unsuccessfully, until a particular configuration stabilises. This was confirmed in interviews, informants saying that there were regular structural upheavals in the ORGANISATIONS involved in the road project as it progressed and certain configurations were perceived to be ineffective. The ill-structured nature of the design activity means that a highly specified system of procedures covering all of eventualities of communication in design is unlikely to be useful, because it cannot pre-specify a complete set of instructions for the as yet unspecified problem. This was reflected in the observation that most of the co-ordination activities observed were generated on an ongoing basis and did not follow a global script or systematic plan closely.

Whilst the allocation of work in the performance of tasks was partially made explicit in the SOP documentation, most of the detailed activities involved in the performance of design work were not defined, and involved the spontaneous generation of a computational, or cognitive architecture for the design system. Some of these information processing structures, when consciously reflected upon at a later time, may be recollected as successful by the participants, and used again to give a consistent pattern of action in the occurrence of similar conditions. This stable division of labour may become integrated into a future SOP at a later date.

This differentiation between planned and locally adapted behaviour patterns is similar to the distinction made by Levi-Strauss (1972) in describing the work of 'the bricoleur' and 'the engineer'. The bricoleur makes use of the available materials at hand to create a structure, whilst the engineer pre-plans work before it is begun. However, such an absolute distinction did not appear in the fieldwork. Whilst the engineers made plans and organised resources in an attempt to control the situation (the 'engineering' component of activity), they were also simultaneously engaged in 'bricolage'. This bricolage involved making use of the limited resources available as the environmental constraints became apparent, and adjusting their contingent behaviours to the evolving circumstances at the site.

### 6.3.6 A review of distributed cognition in engineering design

Engineering design systems appear to have several properties used to structure and process information in the world, transforming loosely defined specifications into well-structured problems, moving through the problem space towards a goal state. This recognition that collaborative design involves *problem setting* (also known as 'specification work') as well as *problem solving* is a central, albeit well understood, feature of design. However, the fieldwork demonstrates that the enacted processes and physical representations (within the artefacts) used in problem setting are critical to the problem solving behaviour, and this is not reflected in current cognitive theories about design.

In the fieldwork, problem setting activity determined how the representations developed for problem setting activity were created, and entered the computational process as inputs to be transformed into an eventual design solution. Problem setting activities therefore pre-specified the representational media used and thus shaped the information processing activities that were applied in subsequent problem resolution. The inclusion of problem setting as a part of design means that no single type of activity can be said to characterise design: any activity determining the course of the process has to be considered as 'design work'.

In the course of design, the computational architecture of the functional system was organised, and organised itself, to allocate sub-tasks between individual agents.

Design information was structured in artefacts, and these artefacts co-ordinated the activity of the collaborating agents. Transformations on the artefact changed its representational content, either by re-structuring the artefact, or by moving the representation to another medium, which would in turn determine the future information processing activity that could be performed on it.

Just as cognitive work in engineering is distributed over different agents and artefacts, so it also has to be brought together again. In the field studies, the individual sub-task design solutions had to be re-integrated with the design as a whole. In the case of ConsCo, the temporary work designs had to be integrated with the design of the road, and in the BEG, the structural, and mechanical and electrical components of the building design had to be reconciled (Appendix B). However, during the life cycle of construction projects, the problem specifications for the engineering designs rarely remain static and can change several times. The design workers therefore have to co-ordinate their ongoing actions to maintain the coherence of the global design, ensuring that all of the component parts remain compatible with one another, despite any changes. The design workers therefore had to make their work visible to their co-workers, even after sub-task allocation, so that they could check that their work was still compatible with the other elements of the distributed task. In the construction team, this was facilitated through sharing a common work space with visual and audio access to the others engaged in the collaborative task. In spatially distant collaborative situations, other more expensive (in terms of time and effort) strategies were applied, in meetings, telephone conversations, letters and the dayfile.

To ensure that the proposed designs were able to meet the problem specifications, as well as being designed safely and according to engineering principles, bottom-up and top-down processing of information was performed by the design system. This involved abstract information specifying the structural phase of design being passed 'down' to the constructors, but also information passed from the construction workers 'up' through the ORGANISATIONAL hierarchies towards the structural phase engineers.

Both top-down and bottom-up processing were evident in the design process, top-down information emanating from the creators of the drawings, and bottom-up information generation, from the construction workers. This meant that a design could be developed that met the problem specifications, but was also appropriate for the construction setting. In the example of ConsCo, bottom-up processing occurred when the construction teams set the problem specifications for the design engineer, provided feedback on the appropriateness of their design representations, and explained how construction events scheduled for the future would interact with the temporary work designs being generated. 'Top-down' information processing occurred when the design representation (symbolised in the drawing), was gradually transformed into instructions to undertake physical operations on materials.

Several properties of the distributed cognitive design systems were derived from the fieldwork. These are discussed below:

• **Sequential action:** Pipelining of activities led to the sequential movement of artefacts through the system, so that the output of one activity became the input of another. There were interdependencies amongst the representational tools used, forming 'suites of tools': design artefacts used could not be examined independently as components of the process, because several were used in combination with one another.

• **Human mediation:** Representations were brought into co-ordination with each other through human action, as they were perceived by agents, operated upon, and transformed into an output in another medium. In ConsCo, the temporary works co-ordinator interpreted the construction team's design specifications, and re-represented the mix of sketches and verbal material as a new document, the design brief. This human mediation meant that knowledge could be distributed across the design process: whilst the engineering design process appeared to involve six independent phases, these phases were interrelated because design workers in one phase were involved in others. For example in ConsCo, problem specification was performed by the same people involved in implementation. This allowed a degree of continuity in the process, and meant that knowledge from one design phase could feed effortlessly into others.

• **Planning and contingency:** Officially sanctioned divisions of labour are described in ORGANISATIONAL documentation, in the SOP schemes. However, these are supplemented by locally determined, socially derived organising systems. These socially determined systems are highly adaptable to their contexts of action, and allow unexpected situations to be managed without complex planning arrangements. Both are important in the co-ordination of activity.

• **A structured environment:** Processing of the representations was not performed in a 'natural' environment, but through an artificially contrived system (i.e. one that was pre-organised) that co-ordinated the individual elements to form a part of a larger cognitive system.

• **ORGANISATIONAL structure:** Knowledge of the ORGANISATIONAL hierarchies by the actors (particularly apparent *within* ORGANISATIONS), meant that it was possible for the design workers to know who to communicate with, to transmit artefacts to, or where to discover relevant information from. Thus the graduate engineer knew that the senior engineer would need to see the problem discovered with the gradients (section 5.5.2), and the senior engineer knew that this would have to be relayed to the resident engineer and the design co-ordinator.

• **Common knowledge:** Although individual agents have responsibilities for particular tasks, they can often comment on, amend and if called to, duplicate the work of others. This was simplified in the engineering systems observed through the use of common artefacts that were accessible to people other than their creator and end user.

• **Common design objects**: In the process of collaboration, representations undergo change. Some of these changes are permanent, leaving traces on their media, and these can be used to track the history of the collaboration. In the fieldwork, drawings and other physical design representations were amended, annotated and archived so that a 'memory' of the design and state of the design process was captured. This allowed the formation of a project 'design rationale', where the current state of a process as well as its historical and future developments was made commonly visible. This visualisable design rationale allowed the participants a better understanding of the process as they collaborated, because they could use it as a resource to generate a shared model of the design process (Perry and Thomas, 1995), because it made explicit the reasoning behind the decisions taken. The process of generating a design rationale was labour free, because the artefacts were created, maintained and archived as a matter of course.

• **Project memory**: The 'project memory' within the systems studied was dynamic, and not located in a single individual or artefact, but distributed throughout the design system. This was maintained through *communication*, as the agents 'reminded' each other what to do by providing representations to each other when required (e.g. in pipelining activities), rather than having to actively seek out information themselves.

• **Graceful degradation**: In the systems observed, there was a great deal of redundancy in the representations used. These existed with all, or partial duplication of information in several media and often in multiple copies (in both humans and physical artefacts). This allowed a property noted in PDP systems: graceful degradation of performance (Rumelhart *et al*, 1986b). This meant that systems did not fail critically when a single processing component failed, because other media (artefacts or agents) were able to represent or transform the required information. The existence of multiple representations within a system also meant that cross checks between the representations could be made (known as 'assistive redundancy' - Hutchins, 1995b).

## 6.4 Developing collaborative technology for design

### 6.4.1 Technologies to support collaborative systems

In distributed design work, elements of the task were shown to be highly interrelated with the co-ordination of the work. Technological developments introduced to the design system must therefore not be allowed to disrupt this delicate framework of interactions. Whilst functional systems for design appear to be adaptive (as has happened with the adoption of technologies like the telephone and the facsimile machine), more intrusive technologies that *impose* an organisation onto the functional system have the potential of also reducing its computational power. It is important to avoid this.

The primary aim of the thesis is to expose the mechanisms used in co-ordinating the work of collaborating designers. Whilst this research is primarily intended to be used a resource to assist developers in understanding the nature of collaboration in engineering design, various developments can be derived from the analysis. This section links the co-ordination mechanisms examined earlier, using them to suggest novel technological infrastructures and configurations. The development of an appropriate configuration of technologies is as important as the development of a new technology in itself, because how the technologies are used in combination with one another and interrelate with the task is critical to the design work.

In the following sections, several new technologies are suggested. Unfortunately, it is not possible to specify this technology to a high level of detail. In most cases this would not be appropriate, because of the different existing technological infrastructures and work contexts that these technologies would be introduced into. Nevertheless, this section covers the proposed technologies in sufficient detail to support the process of preliminary development. Some of the technologies described below have already been implemented in a project involving the development of technology to support aspects of engineering design in construction (CICC).

### 6.4.2 Supporting ORGANISATIONAL and social processes

The ORGANISATIONALLY specified systems of design are intended to provide a method for *controlling* the design process, and are embodied in the structured approach of the standard operating procedure (SOP) systems. However, managing these systems was a long, time consuming and problematic process in both of the ORGANISATIONS examined, to the point where a great deal of time and effort was spent maintaining them. Particular problems occurred with the enormous quantities of information circulating as paper and other documentation. This was evident in the bulk of the dayfiles, which in the case of the road building project (for several construction teams) filled a 'lever arch' file every day. The consequence of this information overload was that paper based design documentation (although not the drawings) was awarded a low status by the designers, because time limitations meant that they could not access it often enough for it to be of use.

In both case studies, engineers were required to read the dayfile, but in reality, they read the dayfile selectively, ignoring much of the content because of redundancy in the information; faxes could be included up to three (or more) times, and most other information duplicated. In general, paperwork moved extremely slowly through the ORGANISATIONS, held up in the postal system, and in the manually maintained document control systems. This was not a problem for simple notes, but for messages that had to be passed backwards and forwards several times, the total time lost in transit could be a major problem for communication.

The main ORGANISATIONALLY determined controlled medium of design representation was the drawings: whilst these captured the physical aspects of the built design, they did not encapsulate all of the features of the "design knowledge", which was distributed across the design workers and other artefacts. Knowledge "in the designers heads" was used to interpret symbols on the drawings, and in many cases, the drawings only specified a design to a limited level of granularity: in the BEG (Appendix B), electrical drawings did not specify the exact equipment to be used, which was left to a subcontractor to interpret. Design knowledge also existed in the documentation that accompanied the drawings, such as the specifications of the manufacturing and construction techniques to be used, or the expected costs of manufacture and maintenance. This integration of the drawings and the peripheral knowledge used to interpret the drawings constituted 'the design' at any given stage. The link between the drawings and the distributed knowledge in the heads of the design workers, the documentation and the situation that they were to be implemented in was managed through socially mediated protocols - it was not possible to fully specify the design process within a set of formal procedures.

There has been a great deal of work on developing an understanding of how ORGANISATIONAL work processes can be changed, in the workflow and business process re-engineering fields (Bowers, Button, and Sharrock, 1995; Randall, Rouncefield and Hughes, 1995); similarly, there has been an interest in informal processes of work and communication, one of the reasons behind the development of CSCW. In the studies developed in this thesis, a range of socially and ORGANISATIONALLY mediated methods of co-ordination were used in to maintain an effective division of labour between the collaborating design workers. Indeed, the amount of communication taking place through socially managed media - the mediating artefacts - suggests that the focus on developing technology in the primary artefacts of design, such as the drawings and schedules (for example in 'shared CAD' technologies), may be misplaced. A more substantial impact on increasing the effectiveness of the design workers could be gained through re-focusing this effort into the development of technologies to support socially mediated co-ordination activities around the primary artefacts (Perry, 1995b).

The *ad hoc* nature of design work is a problem in developing systems: managers like to have formal systems that can be demonstrated to capture the optimal configurations of resources to solve problems. However, even where rules exist, work is rarely performed in this way, because of the different design problems, contexts of action, skills and tools that the design workers have available to them. Any approach to formalising the processes of design work are therefore likely to frustrate the workers and hinder their efforts. Integrating the ORGANISATIONAL and social aspects of the design systems with technological support would appear to be a far more fruitful approach to systems development. However, this would mean that the managers who determine the nature of the ORGANISATIONAL systems would also have to investigate the informal systems and become involved in the development of assistive technologies.

Within the CICC project, this linking of ORGANISATIONAL procedures and informal practices has resulted in the development of a 'person and information finder', known as the 'PIF'. This is a hypermedia system that allows the users to browse information in the ORGANISATION, according to a number of features. They can access information through a number of dimensions - through ORGANISATIONAL hierarchies and by ORGANISATIONAL status; it allows people and information to be searched for through their spatial location in the workplace, through on-line representations of the different workplaces (Rosenberg, Perry, Levers and Farrow, 1997). The PIF is also intended to link into the design model (in the project CAD system), and the people responsible for components of the design will be able to be contacted from hyper-links in the CAD drawings. In the same way, the design workers' are represented electronically on the system with personal 'home pages', giving contextual information about themselves, and electronically linking them with the design models that they are engaged in developing.

### 6.4.3 Supporting ORGANISATIONAL and inter-ORGANISATIONAL activity

Design activity can take place across different individuals and groups within an ORGANISATION and across several ORGANISATIONS. Whilst it is relatively simple to specify systematic procedures (in the SOP) within an ORGANISATION, coupling such operations between ORGANISATIONS is more complex. The SOP systems in use within an ORGANISATION may be highly individual, and retaining and maintaining these practices may be commercially important to them because it may be this that gives them a commercial advantage. Where inter-ORGANISATIONAL technology is introduced and is not integrated successfully with working practices and procedures, there may be resistance to using these technologies, because this will involve maintenance of the inter-ORGANISATIONAL systems in addition to 'normal' workloads. This may also cause a clash of interests between loyalty to the ORGANISATION and to the design project. In most cases, loyalties lie with the parent ORGANISATION, and the implementors of such technology need to be careful not to breach these cultural boundaries.

One solution to reduce inter-ORGANISATIONAL conflict is to use an 'open systems' approach to the management of design related information. Information moving 'up' and 'down' the design hierarchy may pass through various ORGANISATIONS. In the case of ConsCo, this occurs 'downstream' between it and its sub-contractors and suppliers, and 'upstream', to the RE; and in the case of the BEG, 'down' to the construction company and 'up' to the client and architect. However, developing an inter-ORGANISATIONAL information system for design should not simply involve integrating the information for all of the ORGANISATIONS in a single technological infrastructure, because this would place its owner in control of the process - a potentially dangerous approach that would lay the system open to the abuse of commercially sensitive material. Failure to incorporate this into new technologies could leave a single stakeholder with more control than at present and may develop into a breakdown in trust and subsequent problems in maintaining co-operation.

Distributing work across several independent ORGANISATIONAL structures means that there is a distributed locus of control for information in the functional system. Distributing the control over information allows the ORGANISATIONS to chose from a range of problem solving methods for dealing with the design problem. This would mean that procedural decisions about the design would not have to be made at a high level of project management and could be initiated lower in the hierarchy. Whilst these decisions may not be optimised in terms of the resources allocated, they are likely to be well matched to the contingencies of the situation, without incurring the costs of developing a pre-determined set of solutions. A single locus of control could lead to a worse allocation of resources than if this control was distributed over the units dealing with design problems that they had experience and understanding of. The design of technology that allows devolvement in the division of labour could make a dramatic impact on the process of design, because it would give the sub-structures of the functional system more control over their own work activities.

The representations used in design processes are likely to be critical in managing the devolvement of control. Flor and Hutchins (1992) explain how good representations allow their users to reorganise information to be in the right place at the right time, and to encode information more explicitly and thus make it easier to process. However, they also have a third function that is vitally important: they can distribute the executive function of the group (Perkins, 1993, p.94) ceding this control function *to* the artefact. Whilst artefacts themselves do not *act*, they are accorded a structure by their users, and this structure is used to determine how the represented material is to be used. The object of work can therefore itself be used to organise the behaviour of the user group. This was particularly pertinent to the design systems observed, because they did not have a single executive determining their activities, and control was distributed over agents within the systems.

The self-organising aspect of the representation also highlights a problem with the development of CAD models. These systems are expected to supersede physical drawings (currently on paper). However, this would mean that the medium of the design representation would no longer be the factor determining what to do with the drawing's content, because all electronic CAD models are physically alike in structure. These changes to the structure of the design representation may result in the loss of its control function. In developing systems to support design activity it is important to retain this aspect of work by providing artefacts that can act as resources in the organisation of activity. For example, the design representations may need to retain their differentiated titles - 'architectural', 'for comment', 'for construction', and sketched. This must be communicated through some quality of the media, for example giving them different colours to clearly emphasise these distinctions. At present, documents with different functions have different physical properties; they can be printed onto fax paper, sketched onto A4 or A5, or plotted onto A0 paper (see also Frohlich and Perry, 1995). Each of these has a different meaning and determines that different actions can be performed on the design representation it contains.

### 6.4.4 Supporting the flow of design

The iterative nature of design has led researchers to develop computer technologies such as shared editors and shared CAD systems that allow rapid collaborative change to a document, some of which are now commercially available. However, these only provide support within the *structural design* phase. The rationale behind these technologies appears to be flawed in assuming that there is a well-structured design problem (i.e. a particular problem exists), and all that is required for its resolution is to gather the 'designers' into a forum where they can generate a solution by bringing all of their understandings into a common arena. Thus we have collaborative whiteboard technologies and group decision support systems (e.g. Steffik *et al*, 1987; Karat and Bennet, 1990; Lu & Mantei, 1993) that simulate or support meetings. Whilst this approach is appropriate for workers within the structural design phase to pass ideas around and negotiate possible design solutions, such technologies do not support 'problem setting'. This study has shown that problem setting is a critical component of design because it determines the initial media of the design representation and its subsequent computational processing. Unusually, construction design may involve more of this problem setting than other forms of design because it is highly concurrent with implementation.

Problem setting is also important because of its role in the 'upward' flow of information through the design system. Whilst the 'downward' flow of design information through the ORGANISATIONS observed was relatively structured and formalised, communication arising from the problems and conditions on the ground was less controlled. If communication problems are going to occur through a lack of control over the construction process, this is the point where they are most likely to occur, and this is therefore an area that requires particular consideration when designing technology to support this activity. Existing technologies fail in this respect, and this aspect of design has been largely ignored by tool developers. For example, schedules may be generated from CAD systems, but there is no clear method for adapting the CAD representation to match scheduling changes (Perry, Condon, *et al*, 1996).

Common artefacts form a part of the process of product design whilst at the same time orienting the participants to the co-operative aspect of their work. This is an example of an artefact being a part of work, while organising that work through its use. Computer technologies designed to facilitate the design process have so far not attempted to link the design artefact to their use in communication and co-ordination. Thus we have CAD systems and email systems, simulation tools and video-conferencing, rather than integrated packages. Computer-based design products need to go beyond the categories of "design" or "communication" technologies, and need to be flexible enough to simultaneously support these two aspects of design work.

Whilst artefacts were rarely thought of as mechanisms for communication when created, they appeared to be used in transforming information from more highly encoded forms into more easily comprehensible terms. This meant that the representations could be used as overviews and discussed as to how they can become constructions. They are cognitive artefacts created by individuals, but adopted as common artefacts to support collaboration. These common artefacts become a part of group work as they propagate a representation through the distributed cognitive system. Designers of cognitive artefacts should not think of their tools being used in isolation: they are used in combination with other tools and other people. This suggests that suites of tools to support this 'representational flow' (Perry, 1995b) be developed so that the representation in one medium can be easily transformed onto another medium.

Technologies to support this 'representational flow' would be useful in allowing the agents to 'pull' information out of artefacts and move them from one medium to another without laborious human mediation to co-ordinate this re-representation. To get the information about gradients off the drawings in the fieldwork (section 5.5.2), the engineers had to closely examine the drawings and manually copy the information about gradient into tables which could be taken into the field and compared against existing structures by matching them against readings taken from the measuring equipment. On other occasions, only a part of the drawing was required - the drawings were information dense, so to prevent confusion, sketches of the drawing were made, containing only the pertinent information. This was highly wasteful of resources, when such information could have been generated automatically, and effortlessly printed out with less room for transcription errors.

In engineering design, work activities have been structured to use particular artefacts in circumscribed ways, both through historical evolution of engineering, and through direct managerial planning, as in the pre-specified SOP documentation. Within these 'designed' systems, tools that demonstrate changes to their structure are specified at particular phases of the design process so that progress can be monitored (e.g. the drawing stamps). These design tools can greatly affect their suitability for joint use. This has been demonstrated in previous work on the 'objects of co-ordination' (section 2.2.4) where the interaction of a tool user and tool may or may not be open to observation by others, depending on the structure of the tool. In the field studies, the design drawings displayed explicit graphical descriptions of spatial relationships. Changes to the design were thus more simple to detect than those on a 'hidden' representation, where manipulations to the represented information are invisible to those working with them (Norman, 1991; Hutchins, 1995a). CAD systems, databases and simple calculators all hide manipulations to their underlying information, concealing the operations being performed upon them. These representational media do not make changes to the visible state of the design representation, and as a consequence are not likely support the co-ordination of multiple agents as well.

Opening up the changes to the structures of the representation to visual inspection at critical phases in the design cycle is important in developing assistive technologies; if these representations are hidden, the flow of the design process will be disrupted, resulting in mistakes or time consuming re-checking. To develop useful collaborative design technologies, systems developers will have to design electronic media that are able to visibly represent changes when they are required for collaborative activity. In some cases, existing media may have co-ordination qualities that electronic media cannot support at present, and may be better left as they are.

### 6.4.5 Developing a technical memory

The distinction between design (the task) and collaborative activity (orienting co-operation) appears to break down at a fine grain of analysis: communication between people is *about* the design, and not distinct from it (Perry, 1995a). Design artefacts appear to exist to perform two inter-linked functions - to plan systems and to communicate understandings about systems (Perry and Thomas, 1995). As a consequence, artefacts are more than simply partial representational steps towards a design solution, but are integral to generating an understanding of the problem. This secondary role of the artefact in facilitating a shared understanding is one that has received scant attention in current computerised tools. Traditional design artefacts do however, provide a mechanism to allow this: drawings can be annotated and discussed. They provide a context for communication, as well as being a medium for the partially computed design information.

In the fieldwork, artefacts were used to communicate design information between people; they also carried the design history with them by capturing a 'technical memory' of the design process that occurred through this communication. These artefacts could be used to support co-ordination between design workers by increasing the shared context between them in their discussions. This memory of the technical design details could enrich the designers by orienting them to the history and the culture of the design project so that they could understand other people's reasons for decisions made. In this way, the technical memory could make the previous states of the functional system explicit, so that subsequent decisions taken could be informed by the conditions under which earlier decisions were made.

The current technical memory of design in construction engineering is currently managed in diverse and disparate systems: text documents are maintained in the dayfile and drawings are maintained in a separate document control archival system. Although these may be cross referenced in some areas (in ConsCo, through a database), they are not generally physically or systematically linked. In addition to this, each ORGANISATION typically maintains its own systems of information and document control, and these are not linked *across* the ORGANISATIONS in the design project. The problem with the existing design memory systems observed was that the bulk of material in the dayfile meant that the information in it was devalued by the design workers. A reduction in the paper produced would have been more useful, because it would enable the readers to be more aware of the relevant design information, rather than encompassing everything relating to the project. Here, there is a clue as to how technology could be used, in generating an individually customised dayfile, so that the design workers who needed information would automatically be sent it. The importance of the information could also be prioritised, perhaps using a colour coding system, so that important or urgent information would be signalled as having a higher status than procedural matters.

Developing the project archives into a technical memory of the project may perform a useful function in distributing the functional system's computational load over time, allowing the re-use of design knowledge. This could be complimented with an electronic search facility to sift through current material relevant to the problem solving activity: some construction sites may generate several tonnes of paper archiving material. Relevant design knowledge could also be gleaned from searching out the details of previous projects to see how similar problems were solved.

The idea of generating a 'design rationale' (DR) has been proposed as a means of allowing co-designers to reach a shared understanding of the design as it develops, and for users to be able to understand the rationale behind features of the design (Timpka and Sjöberg, unpublished). Current DR techniques attempt to allow the design space to be broken down into a manageable set of components. This allows features to be exposed as either vestigial artefacts of the evolutionary nature of design (i.e. possibly undesirable), or as useful components of the design. Current versions of DR allow a semi-formal representation of the design space (made up of a decision space and an evaluation space) to be generated around an artefact (MacLean, Young and Moran, 1989; MacLean, Bellotti and Young 1990). Another DR system, based on hypertext, called gIBIS (Conklin and Begeman, 1988), allows users to capture design rationale during design meetings. Although gIBIS has been described as slow and hard to operate[2], it has been used for a number of years in industry, demonstrating that the reasoning behind decisions is perceived as a potentially commercially valuable asset.

### 6.4.6 Co-ordinating spatially distributed collaboration

The distributed nature of the construction sites and design offices meant that design workers spent much of their time away from their offices and desks. Often they became 'lost' for long periods of time to colleagues who were trying to communicate with them. This is a particular problem in the construction industry because of spatial distance over the site. There is also a dispersed, inter-ORGANISATIONAL aspect to design work that at present entails a great deal of travelling between offices[3]. This may accelerate with the reported industry trend towards sub-contracting and partnership agreements. The distances covered may also increase as more multi-national ventures are planned - another apparent industry trend, itself made possible

[2] Selvin, personal communication.

[3] The dispersal of agents is also a problem for engineering designers outside the construction industry, as demonstrated by Bellotti and Bly (1996).

through advances in communications technology.

The distributed nature of design work in construction has led to a strategy being employed by the design workers who utilise a great deal of asynchronous media. Representations such as paper based notes, faxes and telephone messages left with colleagues are used to maintain the co-ordination of the spatially distributed collaborative work. In several of the cases observed, the communicants both worked away from their offices much of the time, and continually bounced messages would be passed from site to site as each person replied to earlier messages, and having to leave a message in return, a phenomenon known as 'playing telephone tag'.

In some cases, asynchronous communication *was* supported by technology, via the fax, answer-phones, voice-mail and email, However, because of the generally poor investment in technology by the construction industry, these were rarely used. One possible reason for their low levels of use was that these technologies were not adaptable or useful in the settings that they were used in. For example, physically leaving a message with a colleague of the person they were trying to communicate with could enable nuances to come through that might be difficult to convey in the limited bandwidth available in the asynchronous technologies available. Non-technological media such as a post-it note could be used to convey a message that was not particularly important, or a couriered letter, demonstrating that a degree of formality was being observed. Personal contact on the telephone to a colleague might allow a sense of urgency to be passed on, and would also relay information back to the caller about where the person might be found, when to expect them back, and how important the message was to their work. In some cases, the media used in communication could be mixed to include graphical, numeric and textual representations together, as seen in the example showing how expected gradients differed from reality with an annotated table (section 5.5.2). These features are hard to replicate with the limited functionality of existing technologies.

The technology that such findings suggest, lies in increasing the bandwidth of the asynchronous communication channels, so that complex representational forms could be transmitted. In addition, making available asynchronously accessible information about the recipient would be useful to the initiators of the communication, relaying information about the location, or the work that the recipient was working on. This would allow the sender to access the importance of the communication to the recipient. This information is not possible to obtain using existing technologies for asynchronous communication (fax and email), where the sender has no feedback about the recipient. Novel technologies that attempted to provide this would need to increase the richness of the context of the recipient available to the sender, to allow a more appropriate message to be left in the particular circumstances.

In CICC, the PIF addresses this by providing contextual information about potential recipients of messages, who to contact if they are not available, the work that they are performing in the short- to mid-term, and their past project experience. Screen-shots (captured images of what is on the computer desktop at the time) can be viewed to show what tasks users are currently working on, and 'video-glances' (small, low definition snapshots of the user's desk using an internet camera) allow viewers to see what is on their desks and the other people present. This information gives the communicant a better choice about what to do next - getting in touch with another person, selecting a medium more appropriate to the setting, physically locating that person to meet them face-to-face, or even deciding that the message would not be required.

### 6.4.7 Meetings support

Meetings were the point where design and communication came together most obviously. However, many meetings observed lasted in excess of three hours, and this was described by the informants as too long: accordingly, they became bored and lost interest in the meeting's content. Often, there was an inequality in the value of the meeting for the participants because the information conveyed only moved one way, rather than being mutually beneficial to all of the participants. Inter-ORGANISATIONAL meetings were perceived to be especially ineffective, as too long, unstructured and unfocused. Participants also believed that too many people attended the meetings 'in case anything important came up'. Senior design workers spent a great deal of time in meetings, during which they would often only find a small proportion of material in the meeting of interest to them. One organisational (as opposed to technological) solution to this would be to have more, shorter meetings, with selective participation. This would be dependant on planning ahead and knowing the subject matter of meetings, another point that was felt to be poorly communicated.

A great deal of communication in meetings related to the maintenance of co-ordination between the design stakeholders, rather than communication about the form of the design itself - articulation work. A focus on design, rather than how to co-ordinate the design process would, it was felt by informants, have been more productive. However, although these procedural meetings did not necessarily solve any particular design problem, they served to remind the designers of what the major issues were, they brought those in attendance up to date with the work that had been carried out, and created an opportunity to discuss possible approaches to design problems. In the building design situation at the BEG, these meetings helped to ensure that design actions taken by one group would not interfere with those of the other (Perry and Sanderson, 1997). Meetings were also used as a mechanism for enforcing certain individuals' presence in discussions.

Meetings had a function in pre-empting problems in the ORGANISATIONALLY mediated co-ordination processes. The systematic ORGANISATIONAL procedures of co-ordination were expected to fail occasionally, and meetings allowed people to check up on how these systems were working, and to modify the procedures, either permanently, or to allow 'illegal' actions to be performed under certain circumstances.

This understanding of the role of meetings exposes several areas for the introduction of technology. Meetings appear to be too long: this is because they are hard to arrange, and because people do not want to miss out on important things that *might* come up in them. Desktop video might be useful here: not only could meetings be easily convened, but they could be held more regularly, discussing only the areas of interest of the participants. In addition, these meetings could be easily recorded, and the material catalogued. this would mean that the content of the meetings could be accessed later if required. Records of these meetings could also be incorporated into the 'technical memory' (discussed above), to give an insight into the rationale behind design. However, it is not expected that the virtual meetings will completely replace face-to-face encounters – the medium is not rich enough to support many of the non-verbal components of co-located settings, and electronic meetings are only expected to augment existing practices.

## 6.5 Conclusion

The chapter brings together the findings of the field studies with the analysis, to show how work was co-ordinated in the domain studied. This 'domain theory' about collaborative engineering design in the construction industry is the core of the thesis, but it also has implications that fan out into other areas, covering collaborative engineering design in other domains, and collaborative work in general.

The analysis highlights the interaction between people, artefacts and their configurations. Two kinds of artefacts are distinguished in the fieldwork and appear to be critical components in co-ordinating work - the primary and mediating artefacts, which support the ORGANISATIONAL and social processes of work. The primary artefacts are what is considered to be the artefacts of work, and the mediating artefacts, the structures that are created through social interactions and support the computational actions carried out on the primary artefacts.

The study also highlights the role of context in the design process, which determines the resources that can be brought to bear on problems. Context not only specifies the physical problem situation, but it also specifies the informational resources that can be used in the solution of that problem. These informational resources can be used in structuring the organisation of agents, for example through the layout of the workplace, which can be used to determine the media available to these agents. Context is therefore a major element in specifying the configuration of the functional system.

Distributed cognition is used to highlight the computational features involved in engineering design, and making explicit the organisation of activity. This deeper understanding of the nature of work can be used in developing tools to support the processes described and several tools that could be used to support the design work are discussed. Whilst these suggested tools are not all novel or fully specified, they are likely to be appropriate to the activities that they are intended to support. With the understanding about their roles in the computational processes of design, it is possible to design better configurations of these technologies that can be used to provide an effective set of tools, appropriate to the needs and requirements of the user group.

# Chapter 7

# Conclusions and Issues for Further Research

## 7.1 Summary of the Research

### 7.1.1 Contribution to knowledge

The thesis documents the generation of a domain theory for collaborative engineering design within the construction industry. It draws from field studies to provide data which is analysed within the framework of distributed cognition. This is intended to provide a deep understanding of the mechanisms involved in collaborative design work. The resultant domain theory can be used as a resource for the development of design technologies that are sensitive to work practices and their settings. Analysis delves into the covert, tacit features of work and its situated practice, rather than simply specifying its overt organisation. Explanations of the overt organisation of work underspecify the reality of the work-as-performed, and do not describe the features of work relevant to the performance of the agents involved. In developing technology to support design workers, this level of analysis is required for the development of appropriate technology to augment collaborative work practices.

Distributed cognition is a theoretical framework that can be used to show how information processing occurs in a unit size larger than that of the individual. In this thesis, it was developed and applied in the construction industry to show how groups of interacting design workers interacted with one another, with their environments, and with the physical representations of design to perform problem solving. This approach adopts the methods of social science to explore the microstructure of activity on the task that is involved in the co-ordination of agents and artefacts, and it exposes the social and artefactual dimensions of information processing work in design.

The research demonstrates that engineering design is a vastly complex area. It is inherently multiparticipant, and involves the use of multiple tools. These tools, or artefacts, carry representations that are used by the design workers to both co-ordinate their actions and to perform problem solving activity.

The results of the research provide a rich description of how design work is performed in construction. The analysis reveals how the working division of labour was managed and how context was used as a resource in the organisation of ongoing activities. It demonstrates how communication was used to co-ordinate behaviour, and how this was integral to the performance of the design task. The analysis also demonstrates how the social processes, ORGANISATIONAL procedures, and the local resources and constraints come together in managing the interdependencies between the elements of the functional design system.

The findings revealed in the analysis support the aim of the thesis in developing a deeper understanding about the organisation of activities in engineering design. Through highlighting the mechanisms used to co-ordinate collaborative work, the study reveals areas where particular forms of context-sensitive technology could be introduced that would increase the effectiveness of the design workers. It does this by developing an improved understanding of the role of the tools and the processes in the organisation of design work. The thesis therefore enables CSCW and CSCD developers to better address critical design co-ordination issues in construction engineering. Whilst the research is particularly pertinent the to developers of technologies to support design in construction, it also has a more general application in providing technology to support collaboration in other areas of engineering design.

### 7.1.2 Domain sensitive research findings

A number of novel findings and suggestions for the development of design technologies have been identified in the research, the most important of which are summarised below.

• **Emergence:** The collaborative use of artefacts is central to design and artefacts are incrementally modified to result in a new, emergent design solution. This emergent solution is the creation of a group of distributed actors, rather than occurring through the planned actions of an executive.

• **Formal properties:** The media of the representations determine the possible courses of action that can be followed, because they have formal properties which constrain the range of actions that can be performed on them. Developers of technology need to be aware of the constraints of existing media so that the technologies introduced embody these properties.

• **Boundaries:** Artefacts provide the medium through which design representations are held, communicated and transformed. By exposing the medium that the design representations were held within as a 'boundary object' (Star, 1989), it is possible to see where the output of one worker, or work unit, becomes the input of another. Technologies that make these inputs and outputs compatible could improve the transmission of these representation by reducing the mental effort involved in translating the representations between media. This is an issue of compatibility.

• **Process and communication:** Design is a highly collaborative process, involving several different groups of design workers. The artefacts currently used support the processes of co-ordination between these design workers. However, design aids, such as CAD and computer aided architecture tools are individual user aids, not collaborative tools, and their communicative aspect has been ignored. Design tools that only support the work of individuals fail to support the role of these artefacts in co-ordinating action.

• **Context and co-ordination:** The context of the activity provides a resource for managing the interdependencies between co-workers, as well as setting the constraints on possible design solutions. Agents opportunistically select the medium of communication from the resources within the setting; thus spatial information may be sketched, numeric information tabulated, instructions written, and awareness information spoken. When developing technology, it is important to support this by providing design workers with a flexible and wide range of media for communication. Bandwidth is not always the determining factor in the selection of a particular media. In some instances, low bandwidth communication may prove to be more effective in co-ordinating collaborative action, whilst in others, providing a range of communication methods may be more appropriate.

• **Design work and articulation work:** A clean distinction between 'design activity' and 'co-ordination activity' does not exist. Design work is performed through transformations on the media of communication. Co-ordination cannot be understood independently of the task domain because it arises through interactions with the objects used in communication. The design implications of this are that the media used in work cannot be defined as either 'task based' or 'communicative', and the two should not therefore be developed in isolation from each other (Perry, 1995b).

• **Procedures and practices:** One of the means in which designers are co-ordinated is through standard operating procedures (SOP), defining how workers should orient themselves to each other and to the objects of work. This prestructuring of work is described by Dahlbom and Mathiassen (1993, p.16) as being 'designed to be efficient by minimising direct interaction between individuals and groups. Co-ordination is achieved by having each group or individual follow proscribed rules'. However, the descriptions of work in the thesis shows that these 'rules', or plans, are treated as resources for action (Suchman, 1987), rather than followed by rote. In some situations, there may be no specific rules to follow, and the participants must determine their own courses of action. If systems are developed from specifications derived directly from the SOP, or normative accounts of design, they will fail to recognise the locally organised, contingent dimension to design work.

• **ORGANISATIONAL and Inter-ORGANISATIONAL activity:** Design not only involves the interaction of *individuals* with one another, but also the interaction of *ORGANISATIONS* with one another, which is critical to the performance of problem solving in design. ORGANISATIONS can have different objectives, resources and constraints upon which they operate according to, and technology developers need to be aware of these. If the technologies are introduced across the design system, it is important that they can operate across ORGANISATIONAL boundaries.

• **Adapting to change:** In the construction industry, the design problem is not the only area that must be modified, but the structure of the functional system must also undergo transformation. These structural changes occur as the construction site is developed (through the construction activity itself), and as various ORGANISATIONS or individuals join or leave the project. This change is intrinsic to construction and means that there will be constant reconfiguration to the processes and representations of work.

• **ORGANISATIONS and task decomposition:** Construction ORGANISATIONS lend themselves to task decomposition by structuring their resources (in the division of labour) to break the problem down into smaller units. This 'dynamic reconfiguration' of the functional unit of design must be carefully considered when introducing technology, because the problems faced and resources available are subject to change. Whilst this is particularly applicable to the construction industry, the dynamism of the commercial marketplace and rapid advances in technology means that ORGANISATIONAL change must be considered across all aspects of industry. This is a failing of traditional CSCW, which has not attempted to examine this dynamic, considering ORGANISATIONS as stable entities, rather than evolving structures that adapt to rapidly changing circumstances.

• **Bi-directionality:** The fieldwork shows how information was transmitted both towards construction, in combination with simultaneous feedback from the construction workers. Engineering design in construction is usually described as a top-down process, whilst in reality, other pressures also influence design. Although the flow from the conceptual designers to the construction workers is relatively structured and formalised, communication arising from the problems and conditions on the ground is less controlled. This lack of control means that if communication problems are going to occur, it is here where they are most likely to be found. Technology can be used to support this by providing explicit feedback on the progress of implementation into the structural design phase.

### 7.1.3 An evaluation of the study

The work described in the thesis is both inter-disciplinary and exploratory, and as such, has strengths and weaknesses in its application. These are discussed below:

Examining collaborative activity as a whole, rather than as a set of unrelated processes, requires an approach that is not appropriate for the application of experimental techniques. Qualitative methods can be more appropriately applied to the problem domain. However, the qualitative methods of data collection are less 'precise' than the experimental method. In comparison to the experimental approach, data from the fieldwork is complicated by its lack of control over the variables in the setting, because of the number of people involved, the variability of group composition, and the range of environmental factors acting on the situation. Nevertheless, these apparent weaknesses also form the strength of the approach - the range and number of variables in the field setting are integral to behaviour within that setting. Reducing in the number of variables would establish an artificial situation that could reveal nothing of the organisation of activity in what is a highly complex setting that is rife with interdependencies.

Another problem with the method of fieldwork is that it is highly time consuming. Collaborative interactions typically unfold over days, weeks or even longer; as a consequence, the fieldworker often cannot capture the background to, or the result of, the activities observed. 'Triangulation' exercises (Denzin, 1989; see section 3.6.3) were applied in the thesis to try to diminish the effects of this. Interviews, document collection and parallel studies add depth to the data, drawing information about the activity from a number of independent sources. In addition, several studies were undertaken (Appendices A and B) and their findings compared to strengthen the arguments put forward.

A potentially problematic, but fundamental feature of the study also arises as a result of the limited exploratory power of the methods applied. In the data collection, features other than the representations and processes of the situation are likely to have some bearing on performance on the task. These might include motivational factors or internal politics in the situations studied that cannot be examined through the information processing structures revealed in an examination of the representations and processes of work. Whilst this is an obvious limitation of the approach, by constraining the research to a limited set of factors, the research findings can be applied across settings (Perry, 1997), where these highly situation-dependent factors are not likely to be applicable.

The approach to analysis used in the thesis is not intended to be an exhaustive means of examining the process of engineering design. It would be unrealistic to expect the designers of technology to take the research described and apply it directly into technology without regard to specific situations of use. Indeed, the situations studied were not going to be those in which technology was going to be applied in. Consultation with the managers and workers would be expected to be undertaken as to the implementation of the technology and how these situations could be supported with technology appropriate to the setting; this study could be used to highlight areas to which particular attention should be paid. Again, it is important to emphasise here that the approach used is intended to compliment, and not replace conventional, existing software development approaches.

The study has indirectly demonstrated the problem of relating the analysis of data directly onto systems development. Transforming descriptions of design into prescriptive suggestions for the development of technology is not feasible because requirements capture and social science both strive for different results. However, this is not to say that they are incompatible (Goguen, 1994). As social scientists, we attempt to explore the patterns of activity in settings; requirements engineers attempt to '"capture", "specify", "elicit", or "construct" requirements' for determining the form of a technology (Jirotka and Goguen, 1994). This problem is a common feature of CSCW research and it has not been possible to identify a single instance where a successful commercial technology has been developed directly from such research. This research is not intended to directly breach this divide, and where the development of novel technologies have been discussed, this has been used to help explain the co-ordination of activities, or as a means of opening the discussion about using technology for organisational change.

The thesis and its accompanying publications address the interdisciplinary issues arising between research from field studies of ORGANISATIONAL activity and their application in systems design. This interdisciplinary involvement is a complex area, and one that has only recently been opened up in the field of CSCW, to which knowledge base the thesis adds. The contribution of this research is in exposing the co-ordination of design activity through the resources available to design workers. It performs this by providing a representation of work to support the development of technological resources for construction settings. Developments in the CICC project arising from the thesis are a testimony to the success of the methods used and demonstrate that there is value in this form of research to systems design.

## 7.2 Issues in collaborative design

### 7.2.1 Expanding classical conceptions of design

Design is typically thought of as a creative experience involving leaps of the imagination; engineering, on the other hand, is generally perceived as a non-creative activity, where processes are enacted and standards are applied. It is no coincidence that the verb 'to engineer' is synonymous with the words 'plan', 'manage', 'arrange', 'direct' and 'supervise' (Oxford English Dictionary). These are not words generally linked to inspiration. However, when the larger functional unit of the design system is taken, new and original design solutions can be generated *emergently* through collaborative interaction around these relatively methodical practices.

Previous research in design theory is synthesised and augmented in the thesis, leading to a novel understanding of problem solving in design that has particular application to the development of tools to support the design process. Design is constituted through the interactions of collaborating individuals, where the context of activity and the artefacts involved are a major component of this design activity (Bucciarelli, 1988, 1992; Schön, 1983). These individuals are organised into a unit with particular divisions of labour (Simon, 1973), where they perform task decomposition (Alexander, 1964).

Whilst studies have been made of small groups using tools, they do not have a pre-organised division of labour (Schön, 1983), and in organised groups, artefact use is not generally considered (Simon, 1973). This previous research examining the conjunction of social interaction *around* artefacts has tended to under-emphasise the number, diversity and interrelationships between the artefacts used in the design process. Drawing detail from the fieldwork, the analysis had demonstrated how a wide range of artefacts were involved in composing the design situation. The artefacts may have only been involved in a part of the process, in the background or the foreground of activity, and they may have been combined together in the process of reaching agreement on aspects of the process, but the design process cannot be fully understood without reference to them, because they constitute the *media* through which information processing occurred.

Current design theory does not attempt to link these features into a single framework. Moreover, none of these theories have been directed specifically towards the development of technology to support the design process.

### 7.2.2 The media of design: representations and artefacts

Representations are commonly associated with the process of design, in the media of sketches, drafts, plans, maps, tables, charts and the plethora of other forms that make up the tools of design work. The fieldwork demonstrates how the representations of design are generated and transformed within artefacts, and how different artefacts are used in different parts of the design process.

Artefacts form a physical interface between agents in the design process, mediating the co-ordination of collaborative design. As commonly accessible representations, artefacts allow people to interact with one another *through* the objects of work, rendering the collaboration visible in the state of the artefact itself (Heath and Luff, 1991; Robinson, 1993a). Many of the artefacts used by the design workers in the field studies augmented co-ordination in co-present encounters. These included drawings that could be pointed at and sketches that could be collaboratively generated, modified and annotated. When proximally located, 'peripheral monitoring' was used to identify changes to artefacts (Heath and Luff, 1991). Other artefacts supported co-ordination between spatially distant collaborating design workers. This occurred through the monitoring of other people's work through the artefacts used. Examples of these included the drawings and sketches that were posted and faxed between co-workers. Co-ordination could also be managed through deliberately planned systems that exposed the results of actions performed on artefacts (Bannon and Schmidt, 1991), such as the stamping and signing systems used to control the drawings.

Whilst individuals may make up the component parts of the design process, they cannot deal with the complexity and range of work required on large projects. Specialisation must occur through the division of labour, and the co-ordination of these individuals will determine the success or failure of the design. Representations are the glue that holds groups of collaborating individuals together to co-ordinate their individual actions. In engineering design, there is a range of media to represent the features of the designed object (the primary artefacts), and these are supported by other representations that bring the work of the collaborating workers together (the mediating artefacts). These mediating artefacts support features of the design that are not expressed in the primary media themselves.

In the fieldwork, the process of design was bound up with the generation of primary artefacts representing the state of the design at a given moment of time, for a particular function. Change to the design was effected through the modification or generation of new artefacts, which were used as devices for passing representations around the design system. By transmitting the representation across different media, computations were performed on the represented information. However, whilst the artefacts embodied constraints that determined the transformational computations, the artefacts did not themselves co-ordinate these transformations. These changes to the media were co-ordinated through social and ORGANISATIONAL structures.

The co-ordination of changes to the design artefacts was most noticeable in meetings, when drawings were taken out and discussed. This process did not take place directly onto the artefacts, but was mediated through social interactions between the participants. These communications allowed the information represented in the artefact to be extracted, transmitted using language and gesture, modified, and retransmitted until agreement was reached, whereupon, the artefact could be modified. Artefacts were therefore generated *by* discussions between stakeholders as well as well as forming a resource *for* that discussion (Perry and Sanderson, 1997). The design representations constituted a socially constructed vehicle expressing the negotiated design specifications of the problem. Through these social processes, the problem specifications were made explicit, and an common understanding could be reached, transforming an ill-structured problem into a well-structured one.

Whilst the drawings captured the physical structure of the design at a given stage, they could not, in either of the studies, have been said to encapsulate all of the features of 'the design'. This was distributed across knowledge in the designers heads and in other physical artefacts of design. Knowledge 'in the designers heads' was used in the interpretation of symbols on the design representations, because in many cases, drawings only specified designs to a limited level of granularity. 'Knowledge' also existed in the documentation accompanying the drawings, specifying non-spatial relationships, such as the manufacturing and construction techniques to be used, or of the expected costs of manufacture and maintenance.

Only through gaining a deeper understanding of the role and qualities of the representations used in design can we understand the mechanisms co-ordinating design work. In turn, this can be used to generate a better understanding of how to provide technological support for collaboration between engineering design workers.

## 7.3 Issues arising from the research

The operation of groups engaged in problem solving is hard to conceptualise, because of the range and complexity of the factors that are inherent in the activity. Until recently, there has been no single coherent framework with which to examine collaborative behaviour, integrating individuals, social interaction, tools and technology, and ORGANISATIONAL structures. DC provides this framework through the use of the techniques that cognitive science has so successfully revolutionised the understanding of the individual in psychology. However, traditional approaches, such as GOMS, TAG, task analysis, and experimental approaches to the study of work that have developed from cognitive science have so far ignored the critical influcnce of the environment on behaviour. Because of this, they have failed to capture what this research identifies as central features in the organisation of activity. Behaviour *cannot* be divorced from its situation, and empirical examinations of complex, multiparticipant activity must therefore involve 'in situ', or naturalistic research.

The cognitive perspective of the individual user performing various tasks at the interface is not a good conceptual framework for the development of ORGANISATIONAL technologies. In the real world of work, people interact with each other, and with objects in their environment besides the computer. The framework of distributed cognition has been developed to provide an explanation of problem solving that goes beyond the individual user to include other aspects of the wider activity. The approach analyses the co-ordination of different components of the functional system, including the people involved, their relations to each other, and the representational media used in communication. In particular, DC shows where context is used as a border resource (Brown and Duguid, 1994; Hutchins, 1994) in the organisation of work activities by identifying the 'invisible' resources in the settings used to co-ordinate collaborative action.

The analysis of system behaviour in terms of the representational and computational capacities, affords a rigorous approach into how situations are described and processes documented. The DC approach draws from Simon (1981) in postulating that humans are simple organisms that are good at manipulating their environments (external representations) to achieve goals. To analyse human behaviour, you cannot therefore simply attend to 'cognition in the head' of an individual: the human–artefact system must be considered as a whole. When in a social group, people draw not only from the tools that they use but from the behaviours of other people. Thus people and artefacts must be considered together in a single unit of analysis. This system-level explanation of activity is explicitly cognitive: its concerns are on the representation of information within the system, and the propagation and transformation of these representations in performing a given task. However, the focus on external representations (the design artefacts), and the interactions of individuals (social and ORGANISATIONAL) in the propagation of these representations can give system designers novel insights and a useful perspective in the development of technology to support this work.

## 7.4 Conclusions drawn from the research

The analysis is the result of a study of cognitive processes in an engineering design system within the construction industry. Empirical work into this area has demonstrated that it is possible to describe both the performance of work and the mechanisms of co-ordination within the same analytical framework. The framework was applied to show how work was distributed over a diverse range of representational forms, and was co-ordinated through a variety of social practices and ORGANISATIONAL procedures. As a result of the analysis, the thesis introduces and defines a new concept of 'design' in the process of engineering. It is an emergent process arising through the social interaction of multiple actors in a setting rich in representational artefacts and other organising resources.

The fieldwork and analyses documented in the thesis demonstrate that engineering design is a far more complex activity than assumed in the literature on design. It shows *how* co-ordination is achieved between collaborating designers performing their working within a setting. The design process involves more than a single individual working alone, or assisted with a single or a limited array of artefacts. Because it is a cognitive activity, the problem solving element in design cannot be something that can be understood in simple observations of the social processes involved, as anthropologists and sociologists might attempt to do. The study demonstrates that design involves a number of individuals, each of whom are responsible for elements of the process organised through a division of labour that is mediated through social, ORGANISATIONAL and artefactual structures. The communications that occur between agents in the functional design unit both orient the participants towards the work of each other, as well as transforming the design representations.

The framework developed and used in the thesis has allowed the analysis of empirical studies within the terms of cognitive science. Descriptions of collaborative work in these terms can be used in cognitive engineering, in the development of novel technologies to augment the design process. The analytic framework and its associated method described in the thesis therefore presents a valuable contribution to the repertoire of analytic tools with which systems developers can use to specify technologies that are appropriate to the needs and requirements of users. The findings generated by the application of the framework have been applied in this thesis to the examination of collaborative design in the construction industry. These findings have led to implications for both future technology development, as well as their current application in the CICC project, that is hoped will be appropriate to support engineering design work in the construction industry.

The distributed cognitive approach to cognitive engineering is a descriptive, and not a prescriptive method for the development of technology. However, it gives technology developers a novel perspective on how work is performed, and it uses a similar language to that used in software development. This is because distributed cognition is derived from the computational metaphor of cognitive science, and it is phrased in terms of the inputs and outputs, representations and processes of work. This is another advantage of the method over other sociological analyses of collaborative behaviour, none of which attempt to use terms that can be understood by technology developers.

## 7.5 Future directions for research

As with all studies of a limited duration and resources, there is a great deal of further work that I would have liked to do in the course of the research. However, this was not possible to do within the PhD, although it will provide the basis for a future lifetime of research. The proposed research derives from two elements of the work performed. The first of these arises from the limitations of the study, in the number and range of settings examined. The other develops the findings of the workplace studies to see how technology developed from the implications of the study will transform the functional systems that it is applied in.

It would be interesting to carry out more data collection to see how this would support the thesis, particularly in different ORGANISATIONS involved in the design process. This might include the involvement of an architect or landscape designers, to see how the 'aesthetic' component of design fits into that of engineering design. The inclusion of other stakeholders, in finance, subcontracting, materials supply, and so on would also give an insight into these relatively unexamined, although potentially critical design areas. In the thesis, the input of these was indirectly observed, and can be seen in the data collection where the stakeholders had a direct link with the ORGANISATIONS under examination. It would therefore be useful to continue this in more detail in further fieldwork.

Another area where more data collection in other areas of design would be beneficial to the research into engineering design would be in other, parallel engineering domains, such as manufacturing. These could be compared to construction, to examine where similarities and differences occurred in the performance of design work. This is partially being undertaken in a cross-cultural comparison of design work with Duncan Sanderson[1] in the manufacturing industry, and although this does not explicitly involve application of the DC framework, some comparisons in work practices can be made. However, this has meant that the mechanisms of co-ordination cannot be directly compared (Perry and Sanderson, 1997), and it would be useful to make this link more explicit.

A further research question would be to examine the impact of the technologies developed from the studies, in their adoption and use in practice, and how this would change the distributed cognitive processes of the functional system. This is currently being undertaken by the author as a part of the CICC project, and a preliminary study is underway. Further research would help support the findings of the thesis, although the development and implementation of these technologies in the workplace is

[1] A senior researcher at ITRI, University of Brighton.

limited because these technologies are still undergoing technical development and implementation.

## 7.6 Endnote

As a concluding note, the work in this thesis echoes Herbert Simon's writing, in 'The sciences of the artificial', where he recognised at an early stage that – 'a deeper understanding of how representations are created and how they contribute to the solution of problems will become an essential component in the future theory of design' (Simon, 1981, p. 132). To do this, Simon claimed that we need to draw from a number of intellectual disciplines to understand how information processing systems are able to function. The information processing systems involved in design activity may not be what we have traditionally understood as 'designers', and may involve - 'a complex of men and women and computers in organised cooperation' (ibid., p. 138). Here, he saw the role of organised co-operation in human activity as a crucial element of work: 'The rules imposed on us by organizations - the organizations that employ us and the organizations that govern us - restrict our liberties in a variety of ways. But these same organizations provide us with opportunities for reaching goals and attaining freedoms that we could not even imagine reaching by individual effort.' (ibid., p. 155). These are the blocks upon which research into design must build, and the inspiration from which much of this thesis draws.

In performing this research I hope to have made some advance in the direction set out by Simon within a specific domain, that of the construction industry. This has involved identifying the representations used in design and examining how these were created and modified, to demonstrate how the systems observed performed information processing activities within their contexts of action. Only by recognising how design systems operate can we begin to understand how best to support their activities with technology, to modify and augment the design process in a manner appropriate to their settings.

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# Appendix A

# Fieldwork: Design Activity in the Workplace

## A.1 Arrival story: a narrative

An 'arrival story' of entering the field to study design is documented below, to give a flavour of the workplace and to expose the nature of collecting material in naturalistic research. It is important to make the issues involved in data collection clear, so that the fieldwork can be evaluated in a manner appropriate to the methods used.

"As I stepped into the hallway to enter the office I could hear the sound of stamping feet, and several voices raised, swearing together, accompanied by a loud guffawed laugh. Clearly this was going to be a different experience to the lab and office based work that I had so far observed. A clod of mud shot across the room, narrowly missing me; the office erupted into laughter. A desk was prepared for me (books and papers on a rickety table were roughly forced to one side), and I was introduced to the group ("This is John: he's a tosser" - what did this mean? Was there really such a craft or profession?).

Over the next few hours, I had to amass a huge quantity of information. Knowledge was rapidly imparted, using terminology that I had little experience of, relating to problems and work that I knew nothing about. Over the next few days, things became clearer; I grew to know the engineers who I had spoken to on that first day, and met the foremen and gangers who organised the physical side of the work. I toured the site and learned something of the process of construction, about pouring concrete and erecting scaffolding. Most importantly, I learned something of the processes of how they organised themselves to turn the abstract designs into structures. What had initially appeared to be a mass of "blooming, buzzing confusion" (James, 1890) began to take on an order that, without living with, and becoming involved with, appeared chaotic and inconsistent. It was not that engineers and other workers operated in a highly structured environment, but that they had learned to operate in conditions of disorder, organising pathways for information and using methods of communication that could cope with the noise and complexity of the site."

## A.2 Temporary works design

### A.2.1 Entering the field

The intention of the study was to understand the work of design in engineering practice, so the study had to track the major phases that became apparent as the ethnographically informed fieldwork unfolded. This resulted in work being carried out at three sites at a construction company and at a single site with a building engineering group (Appendix B). The rationale of the thesis is to examine the process of design, rather than a pre-specified set of designers at a single site, so the distributed nature of the fieldwork, although unconventional[1], was not inappropriate. Within the construction company, the three sites included, the construction site itself, the production support teams that provided technical and material assistance to the construction teams, and lastly the temporary works designers, who developed the temporary structures involved in construction. The consulting engineering group study was conducted on a single site, although meeting were held in other locations. The four groups were studied over a period of eleven months although the studies were necessarily of limited duration. On each occasion, follow up studies, involving a review of the reports written about the fieldwork, were conducted to investigate how the participants viewed the research; their comments were incorporated into the studies and contributed to an improved understanding of work, in addition to being an external control on the validity (specifically, the 'face validity') of the research.

One of the greatest problems in doing fieldwork lies in entering the workplace. Gaining access to a site is an extraordinarily complex and time consuming activity. Negotiations of the value of the study to the observed ORGANISATION are a major part of gaining access, and how this is done can affect the study, even before the fieldwork begins. In this particular set of workplace studies, sponsors appeared in the form of the CICC project industrial partners, who were interested in discovering a 'human factors' perspective on the design and construction process. These sponsors made contacts with employees in their ORGANISATIONS (in general, managers) who were interested in the perspectives of an independent examination of communications within their companies.

In the workplace studies documented in the thesis, it was impossible to participate as a 'participant observer', due to the skilled nature of the work (to which I had no

[1] Traditionally, ethnographers tend to spend large amounts of time at a single site, or with the same people; the reason for this is that they are trying to understand the perspectives of individuals. In this case however, the emphasis is not the individuals, but on the processes that bind a distributed *group* of individuals into a problem solving unit.

background) and because a number of studies were required across a range of ORGANISATIONAL boundaries. The role of the ethnographer was therefore defined early on in the workplace studies as a consultant, and I was associated with the management perspective and as a 'communications expert'. In addition, I was labelled as a computer scientist and technologist, neither of which I wanted to apply to me. Being seen as a management 'stooge' would not be conducive to the open and free access to team processes - in the construction site I was humorously referred to as 'the spy' by one of the foremen, and this was something that had to be disavowed early on in fieldwork. Similarly, as a 'communications expert', I did not want informants to answer questions on, and make available, only 'communications relevant' information, nor did I want to seen as a technologist, who only required information relating to computers. On entering each work site, it was important to carefully make these issues clear to all of the people that I came into contact with.

### A.2.2 Background to the study

The background details to the fieldwork, including the participants to the design process, their roles and procedures they follow, must be made explicit before data from the fieldwork on the design process can be discussed. This contextual information will allow the reader to get a feel for what the design workers are trying to achieve and the resources that are available to them, in terms of the participants, their relationships to one another and the setting. Whilst construction work is partly dependent upon (UK) legislation and accepted civil engineering practices and particular contractual details, some generalisations can be made from the data outside of the fieldwork. Bearing this in mind, the study was not intended as an ORGANISATIONALLY independent (i.e. cross cultural) examination of civil engineering in the construction industry, but as a particular instance of design within a real world setting.

The field study of the construction company (known as ConsCo) involved examining the work of civil engineers and construction workers. Fieldwork was performed in three locations, tracking the design process through the structure of ConsCo. One project was studied, involving a £75 million road building scheme. The 'client' (funding body) of the project was the Highways Agency, reporting to the Department of Transport, who set the initial specifications of the design. The engineering detail and project management was contracted out from the Highways Agency to an engineering company, whilst the construction work, known as 'civil engineering' was contracted out to ConsCo.

For the purposes of the study, the unit of examination comprises of all of the parties involved in the design activity - the functional design system. The activity involved the participation of three distributed units working for ConsCo. Several other ORGANISATIONS also participated in this activity. It is important to note that the *activity* is the determinant of the boundaries of the design system, and not the artificial ORGANISATIONAL groupings. A description of the project, the teams involved and the resources available to the project are documented below, setting the context for the more detailed fieldwork described in the cycle of design.

### A.2.3 The construction site

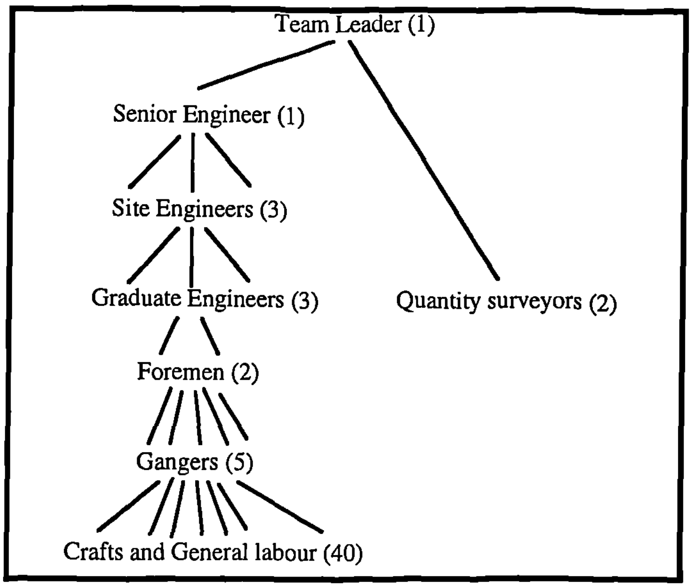
**Goals, relationships and resources**

The construction work on-site was performed by a team of engineers and labourers, aided by quantity surveyors. The task of the team involved building a new section of road through marshland, part of which included a multi-span bridge. The primary goal for the team was therefore to construct the given designs as cost effectively as possible, conforming to the drawings, within the safety requirements, legislation, industry standards and other stakeholder requirements (most notably, those set by an environmental agency, and a railway operator, over whose tracks the bridge crossed). A photograph of the bridge deck under construction can be seen in fig. A.1, which shows an engineer (right of picture) examining steelwork, surrounded by steel fixers attaching the concrete reinforcing 'rebar'. Scaffolding supporting the bridge deck can be seen to the right and centre of the photograph.

fig. A.1. Bridge surface prior to concrete pour.

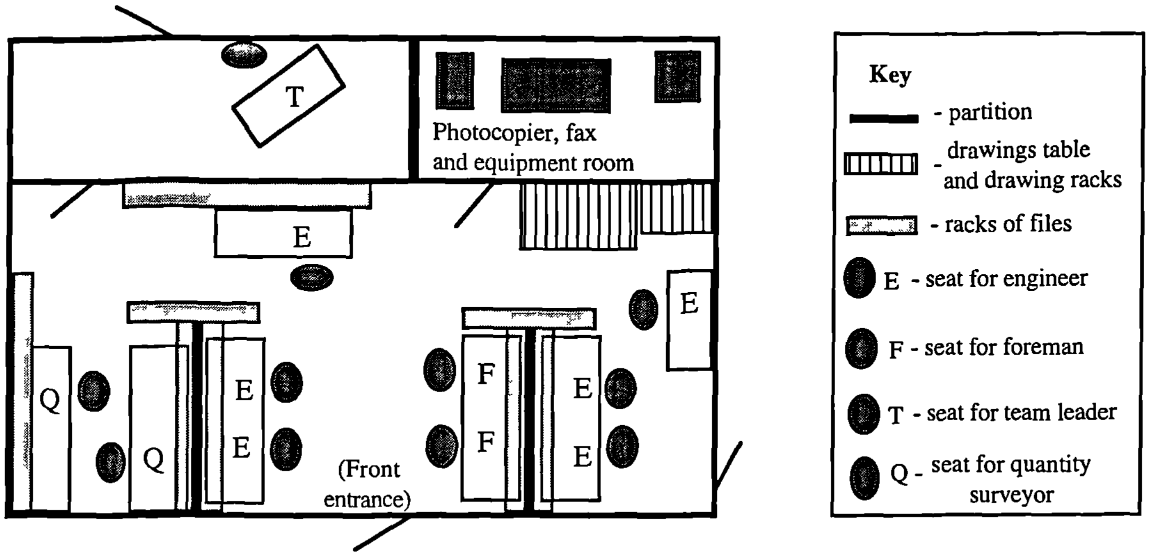
The construction team was located in a satellite office around a quarter of an hour drive away from the main site office, where the construction management and other construction teams operated from. Communication links with this main site were described as poor because of the distances involved. The construction team included a hierarchy (ordered in seniority) of team leader, seven engineers (one senior, three site, and three graduate engineers), two foremen (senior work supervisors), five gangers (junior supervisors), the craftsmen and general labour, varying around forty in number (see fig. A.2.). Two quantity surveyors, similar in rank to the graduate engineers reported directly to the team leader. This hierarchy was important to the distribution, of labour in the group, because it determined the responsibilities and roles that individuals undertook. It also provides an insight into how work was delegated 'downstream' through the team, and how knowledge about site conditions was propagated 'upstream' from the site.

fig. A.2. Hierarchy of seniority in the construction team.




The office was used by the engineers and senior construction personnel, and was laid out in an open plan style (see fig A.3.). The diagram demonstrates how the team personnel could be made aware of each other within this confined space, and shows how they had access to design artefacts (the drawings and files) that could be used as resources for performing their work.

fig. A.3. Layout of construction team office




One of the graduate engineers had an office on the site itself, and only visited the main office in the mornings and evenings. The labourers worked on the site ten minutes away along a half mile stretch of poorly maintained haul road, accessible only by foot or four wheel drive transport (available to the foreman). This distance meant that communication between the construction workers and the satellite office was complicated by spatial fragmentation.

**The construction process**

The design for the original structures of the road was predetermined for the construction team, and was generated by an external ORGANISATION, known as 'the Project Engineer'. The Project Engineer produced design drawings detailing the structure of the 'permanent works' - the finished road and bridge. These showed the final structure of the built design, including the materials to be used, placement of the steel reinforcement, location of the supporting piles and the tolerances that would have to be used. The permanent works drawings set the precise specifications for construction. 'The resident engineer' (or RE) was the representative on site of the Project Engineer; they were employed by the client to oversee the construction of the design. The team had copies of the drawings that it was either working on, or would soon be working on, sent by a document control office at the central ConsCo office on the site.

The project's drawings held most of the design information used to direct the team's activities. The 'drawings' included two forms of representation relating to the road and bridge being built. One set of drawings, the permanent works drawings, were the designs created by the Project Engineer. The other drawings were created by ConsCo, and known as temporary works (T/W) drawings - structures removed following the completion of the permanent construction. These T/W drawings detailed how the structure of the original designs was to be put together: the supports to be used, the placing of concrete moulds, the location of the haul roads to supply the site, and so on. Once the form of the temporary works for construction has been designed, the work of construction could begin. During the fieldwork, the 'temporary works' drawings were the most frequently consulted representations used by the team. Building these temporary structures formed the most time consuming aspect of construction work. Once the temporary works structures had been erected, the permanent structures could be built, involving the placement of steel reinforcement and pouring of concrete. These tasks, whilst requiring a high level of precision, did not did not comprise of a great deal of effort, which was directed at the design, construction and removal of temporary works structures.

An explicit description of the construction process was available to the construction team, known as the 'Contract Quality Plan'. This document described what standard operating procedures to undertake at any given point in the process; in reality, it was hard to find anyone who had read it, and it was several months out of date. As a consequence, knowledge about the team process was localised in the individuals who had responsibility for the particular tasks. Only the team leader and senior engineer had an overview of the responsibilities and tasks performed by the rest of the team. In general, workers were only partially aware of the responsibilities of others, although this was not important to them, because they were aware of the procedures relating to their own work.

**Accountability and Responsibility**

In order to begin the steel work, concrete pours and other general work that make up construction, resources had to be put to work, in terms of labour, plant and materials. The organisation of this work was generally undertaken by the site engineers, and to a lesser extent the graduate engineers. Much of construction work was demand led, and work could only occur when the site had been prepared: materials or other resources might have to be ordered or cancelled at the last minute because the site was prepared earlier or later than expected. The use of different materials in the permanent structures could change the project's specifications and such changes would need to be checked with the RE. Changes to the materials used in temporary works structures meant that these designs had to be checked by the senior team engineer or by off-site temporary works designers.

To demonstrate that the work was being conducted as contracted, the team had to communicate with the RE, and get them to sign a form agreeing to this. This form was used to prove that the construction work has been completed to an appropriate quality level, and avoiding disagreements at a more costly to change, later stage.

Alongside the work of construction, the costs of the work had to be controlled; the team's quantity surveyors performed this accounting task through the production of reports on the team's projected and actual costs to demonstrate that work was being conducted cost effectively, and according to plan. The quantity surveyors therefore had to be aware of the work that the team was doing and understand the materials, processes and importance of the work being done.

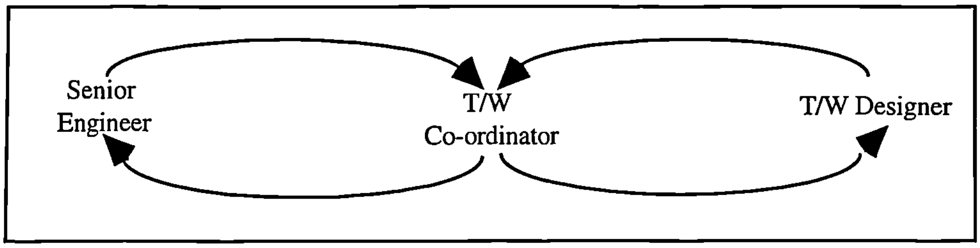
### A.2.4 Temporary works co-ordination

Temporary works co-ordination was managed by the production support (PS) team. The PS team did not operate as a single problem solving unit; rather they acted as an extension of the construction teams, able to organise their activities at a level that the teams themselves did not have the time or experience for, and providing this service for several construction teams on the site.

Three members of the team were involved in the work relating to the construction team studied. These three were co-located in an open plan office in the middle of the main site office (distant to the construction team). Along one side of the room ran a corridor that people entering the site office would have to walk along. This was a deliberate arrangement, intended to increase their contact with passers by. On a weekly basis, either the construction teams visited the main offices and met the production support team members, or vice versa, with a member of the production support team going on site.

The main function of the production support team was to manage communication on the site for the groups involved in the construction process. This usually involved chairing meetings with external ORGANISATIONS, or acting as a proxy for the team when the team members could not be physically present. Their experience with the design of the temporary works structures and the construction work on the site allowed them to understand the problems that the teams faced, whilst leaving them detached from the construction work itself, and in a position to see arising problem situations from both perspectives.

The critical member of the production support team for the fieldwork was involved in co-ordinating the design of temporary works: the temporary works co-ordinator (known as the TWC). The TWC mediated communication between teams and the designers of temporary works: this involved passing the team's requirements on to the temporary works designers or proprietary designers (both remote from the site) and managing communications between the problem holders (the team) and the problem solvers (the external designers) until the designs were completed. The TWC maintained a single route for all temporary works design related information to pass through, thus allowing rescheduling and change to be performed more easily than by the various individuals working on other aspects of design and construction. The work of the TWC entailed them being constantly updated on the current state of the site, and acting as a conduit for filtering and passing on information between the remote groups:




Two other members of the production support team were located in the same room as the TWC. One of these was involved in planning, involving scheduling and programme management. This work involved producing scheduling information, such as weekly work schedules, and critical path analyses that were used to direct the team's behaviour in the long term (over three months). Their explicit function was to provide detailed scheduling advice to teams and to help them interpret what this planning would entail in terms of activities. The work also involved analysis of the construction team's progress reports to see how their ongoing activities matched the work schedule. The other member of the PS team was involved in temporary materials co-ordination. This involved the ordering and maintenance of temporary works equipment (such as scaffolding, concrete moulds and other falsework and formwork) on site, including both in-house and off-hire equipment. The close proximity of these two other people enabled the TWC to be made aware of other temporary works related activities being undertaken at any time.

### A.2.5 The temporary works design team

The temporary works design team provided a design service for the many construction sites that ConsCo was involved with. The main ConsCo engineering office where the temporary works design team worked was a quiet, open plan room, with the engineers working almost silently at their desks in an atmosphere similar to that of a library, and there was relatively little interpersonal communication. Books and other reference materials covered the walls, and the TWDs spent much of their time reading these. The procedures that the temporary works designers were expected to follow were described in a document: the 'Planning and Temporary Works Handbook'. These procedures explicitly set out the relationships between the parties to temporary works design, their responsibilities and proscribed methods of work.

However, it was rarely used and was several years out of date, bearing only a passing resemblance to the activities observed. The main engineering office was distant to the construction site, located about an hour and a half away by car, across London. To communicate with the site, the temporary works design team had fax machines, telephone links, and were able to visit their assigned sites on a two weekly basis.

The construction team collaborated with the temporary works designers when they required designs for temporary works, including items such as falsework, formwork, cofferdams, retaining walls, access roads and bridges, temporary foundations, road diversions and demolition. These temporary works features were not specified in the original designs or drawings created by the Project Engineer, which only detailed the designs for permanent structures. The temporary works generated were required to conform to the safety and quality requirements specified in the CDM (Construction [design and management]) regulations and also to meet the demands specified in the project contract. In addition, the work had to be performed as quickly and as cheaply as possible, to which there may be a contradiction - designs that are quick or cheap to build can be expensive or slow to design, the reverse of which can also be true.

### A.2.6 Other stakeholders to the process

The resident engineer was employed to ascertain that the constructions were proceeding to the designs and according to the quality standards in the contract between the client and tender company (ConsCo). This workload was split up into spatial areas supervised by 'the assistant section RE'. The assistant section RE had a 'man on the ground' checking standards and watching the work as it was being performed - known as the 'clerk of works'. At some stages in the design, construction teams required the services of subcontractors, who performed specialist activities that the team had less expertise in. ConsCo had to inform the RE whenever subcontractors were used; when subcontractors further subcontract with another party, they had to also gain the approval of ConsCo and the RE.

Materials suppliers were involved in the construction process, providing equipment and plant. The materials that were most important to the temporary works process were the 'formwork' and 'falsework' for holding up and moulding the concrete structures. If supplies were unavailable or too expensive, the temporary works designs had to be changed. The suppliers of some specialist materials were also involved in producing designs for work involving their materials, because of their skills and experience in using the products. This might involve particular layouts and configurations of the temporary works materials. These 'supplier designs' might also affect other designs in unexpected ways, because they could change access routes, or require work to be done in a specified order, and possibly affecting the critical path of the project. The teams therefore had to maintain close contact with these suppliers to check that their designs were compatible with existing plans.

Several other stakeholders had a voice in the construction process, and whose approval was required work to proceed. These included an environmental agency, who were required to check up on any watercourse pollution that the site might cause to the surrounding marshland, and a railway operating ORGANISATION, the owners of the railway line over whose tracks the bridge was being built. The railway operators had a particular concern that material would fall from the bridge onto the trains passing below. Each of these had an important say in how the construction process was undertaken.

## A.3 Phases of activity in temporary works design

The six phases in the 'cycle of design' are elaborated on in the particular context of work arising out of the work on the bridge deck of the road building project, alongside examples of problems faced and behaviour observed during fieldwork.

Whilst the phases were seen to be discrete (i.e. they were discriminated at an abstract level), the reality of the situation was that these units were not completely distinct. The reason for this was that the same agents could be involved in several of the phases, and that whilst much of the information relevant to the sequential processes of design described was in the form of controlled documentation, a large proportion of the information relating to the design was retained in the form of mental representations held by these agents. This mentally encoded knowledge about the design was *phase independent* and could be applied in more than one phase.

An important point to note was that whilst the official, formal process of design and construction activity was regulated, an informal, socially based design activity took place in parallel to the official account. This formed an unregulated, mediating activity through which communication that was not proscribed in the official engineering process could take place. Informal, ad hoc, channels of communication were important to the design process because the idealised ORGANISATIONAL procedures could be too inflexible to adapt to the complex and non-standard situations of the real world setting.

The mechanisms used in the two ORGANISATIONS examined are analysed in the terms of distributed cognition, examining the inputs and outputs of each phase of the process and demonstrating the processes (formal and socially managed protocols), the context of the activity, and the representations used in the completion of each of the design and construction phases described in section 4.5.3.

### A.3.1 Information gathering

This phase of activity arose out of the day to day management of construction activity. The information gathering phase of design was a continuous, ongoing process, involving searching out discrepancies between the inputs making up of the construction programme (incorporating the schedule, permanent works and temporary works drawings) and the state of the site itself.

Information relating to the state of the site was collected from the different groups of workers on the site, each using their different skills and experience to determine these discrepancies. Small problems relating to the construction materials would usually be noticed by the tradesmen, who would pass this information to the gangers, where it would precipitate upwards through the team hierarchy to the graduate engineers, who would either record the problem in the works record (this functioned as the site diary - the official record of activities on the site), or as in most cases, they would mention the problem to the site engineers who could determine an appropriate course of action.

Problems at a more global level would be determined by the engineers, based on their patrols around the site (known as 'site visits') where they would see how the activities that they had been previously assigned to manage (by the senior engineer) were progressing. Site visits also provided an opportunity for the engineers to engage in ad hoc encounters with the workers on the site which provided a source of information on any problems developing on the site. An example of a site visit is given below:

> In one site visit, a site engineer was taking a crane hire representative around the site, to discover what sort of crane they would require to place some beams onto the bridge underside - an awkward situation to reach.
>
> Standing under the bridge, the site engineer and the crane representative were joined by a foreman, and as they discussed the section, they pointed up at the bridge area that they were referring to. They deliberated over possible methods of access to the bridge and scaffolding, and other features that would have to be removed or reached over by the crane.
>
> Whilst involved in this discussion, the assistant section RE (the RE's representative on site) saw them and came over. They became embroiled in an (amicable) argument over the method used in a concrete pour on a section of the bridge adjacent to the area that they were standing on. It appeared that the Project Engineer had not specified in the drawings *how* the concrete was to be poured; the team's engineers had decided on a method that was not approved by the RE (although he could not legally enforce this due to the oversight). No answer was reached, but they agreed to continue the discussion at a more convenient time.

```
Continuing from this area and leaving the assistant section RE, two
gangers came over and mentioned that they'd seen the site engineer
talking to the assistant section RE, and they wanted to complain
about his intrusive way of examining their work, which was holding
them up in completing a concrete pour. The engineer noted their
arguments down in a notebook and agreed to discuss the matter with
him when they next spoke.
```

To obtain technical information on the state of the site, measurements of the current state of the site were taken by the graduate engineers using the theodolites and geodometers, which they would take out (called 'setting up') and do the 'chainage' (measuring the positions of the actual structures against the positions of the planned structures). This process was similar to that of plotting a course in the navigation process described by Hutchins (1988;1995a), where physical features of the world would be matched to a chart. Information collected on the location of structures would be noted onto tables of chainage and returned to the satellite office, where they would be matched to the drawings to see whether the structure was sited correctly, and the schedule could be signed off as a task completed.

Several artefacts were used on the site in information gathering. The schedule catalogued the order of actions to be performed: this was broken down into the contract programme, which detailed the work to be performed over the three year duration of the project. The contract programme was broken down into a representation delineating the teams expected activities over a three month period, known as the stage programme, and finally the weekly work schedule, which was generated by the team leader and senior engineer. This broke the activities described in the stage programme down into individual responsibilities for the gangers and foremen who supervised the labour.

The temporary and permanent works drawings were used to see what form the designed structures were to take and to determine the work involved in their construction. These drawings were used as diagrammatic representations that could be compared to the final built structures to see if they had been constructed correctly, as well as indicating what future work would have to be performed. One such situation was observed in a discussion between an engineer and a ganger who were discussing a conflict over the observed construction and the drawings:

```
Ganger: 'You know that on the drawing?'

Graduate engineer: 'No.'

Ganger: <pulls out drawing onto desk> 'You see there?' <points at
feature on drawing>.

Graduate engineer: 'That's the height of the parapet'.

Ganger: 'Aha! Yeah.'.

Graduate engineer: 'OK. So you start there...' (points at same
feature of the drawing as the ganger)...'Ah...Err...'<mumbles>
```

Ganger: 'You see?'.

Graduate engineer: 'Yeah.'

Ganger: 'It comes square to the top level...'

Graduate engineer: 'Just over the lighting column there...'<mumbles inaudibly>.

Ganger: 'An that's two metres there eh?'

Graduate engineer: 'Yeah.' <taps an area on the drawing with screwed up expression on his face>.

Ganger: 'It's only a metre to the top of the box'....'Yeah, know what I mean?.

Graduate engineer: 'OK...'

Ganger: 'Do you wanna come up on the deck an' have a look?'.

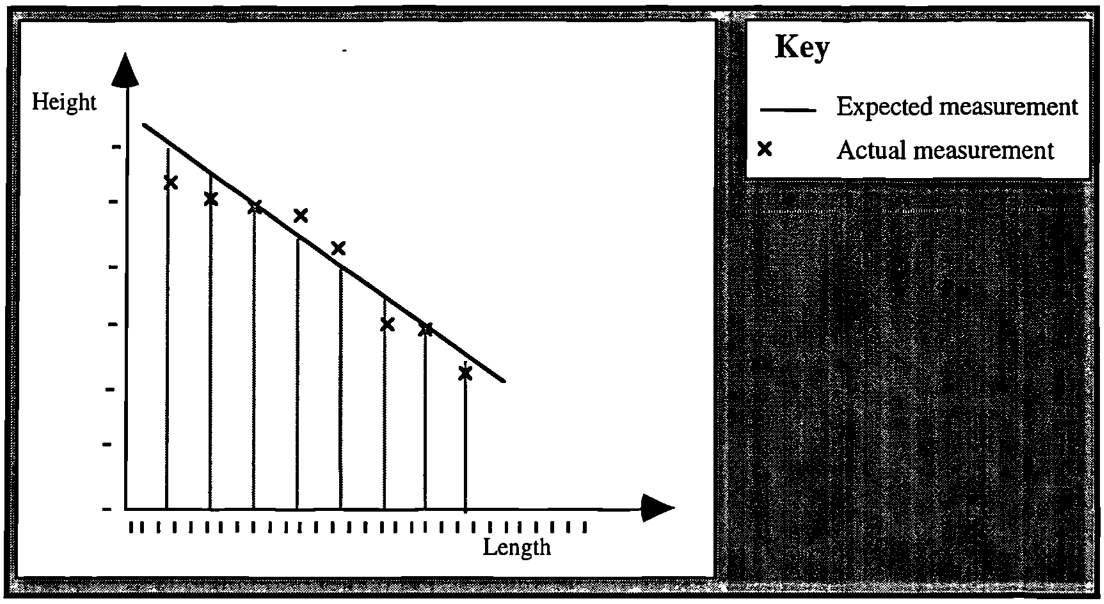
<They leave for the site soon afterwards>

Here, the discussants use the drawing as a means of comparing the gangers expectations of what the temporary works structure should look like to reality on the site. The ganger has noticed a discrepancy in the match between the drawing and the his observations: 'the parapet' should be two metres from 'the box'; it is, in fact, one metre. The drawing is used both as a means of gaining a better understanding of what the structure should look like, and as a means of communicating and discussing this with the engineer responsible for managing its construction. They then go on site to show the engineer the situation as it stands.

It was common for sketches and tables to be generated from the drawings because the drawings were often too large to take on site and over-complex for particular tasks. Re-representing the relevant information into a simplified media could enable simpler and more easily visualisable comparisons of data sets. An example is given below of how transforming a drawing onto a graph could aid understanding:

A graduate engineer had spent several minutes poring over a drawing taking measurements of the gradient of the surface of the bridge ('the deck') onto a hand drawn table. These measurements were then transferred onto a sketch, but in a different format to that of the original drawing: whilst the original drawing had been an overview of the deck (viewed from overhead), the sketch was a section through the structure (viewed from the side). In addition, the axes on the sketch were chosen so that they exaggerated the gradient and made deviations and discrepancies in the data more easily visible: the horizontal axis was on a scale of 1:250, whilst the vertical scale was 1:10. The sketch was then taken onto the site and real measurements were annotated onto it as they were taken (see fig. A.4.).

fig. A.4. Sketch of road gradient.




The sketch had been taken out into the field, and annotated so that the measurements taken with the geotechnical equipment could be annotated onto it. The sketch clearly demonstrates that the measured slope had a gradient that did not match the gradient on the drawing. The form of this representation clearly demonstrated this, as the difference was exaggerated through the differential scales on the axes.

The reason for this discrepancy was that a sub-contractor had driven the piles to incorrect tolerances, the discovery of which had important consequences on subsequent building activities because it limited the loading that could be placed on them.

The outputs of the information gathering phase were held informally in the heads of the engineers, foremen, gangers and labour as general information about the site. Other artefacts were used, including the officially sanctioned works records, as notes and memoranda on desks and in files, and as the 'back of an envelope' type sketches that the engineers took to represent spatial relationships between objects that were hard to describe in text. These sketches were rough, hand drawn, and captured selective information that was not immediately discernible or available from the official records of the construction process. These roughly created artefacts were often annotated with text and numbers over time, and were used as personal records or in conversations to demonstrate a concept to other people.

Each engineer would have many responsibilities, but only through bringing these together could an overall picture of the site and plans for future activities be generated. An overview of the project design requirements was performed by sorting this information into meaningful units so that problem specifications for temporary works could be set, and design requirements drawn up. This took place in the next phase of temporary works design - information collation.

### A.3.2 Information collation

Information collation involved the transformation of knowledge (from the information gathering phase) about the state of the site into a representation of the problem that specified it in a way that could lead to a design solution. This involved organising the raw information obtained from the site into a form that could be used in problem solving. The process involved bringing together information about the site from a number of sources, and distributed over a range of personnel, into a coherent and organised form that related to a particular proposed design feature.

The inputs to the information collation phase of design incorporated the outputs of the information gathering activity. In practice this process involved communication between the different people on the site who held information about conditions on it, determining *what* information was related, and *how* it was related. Because designs had to be relevant to the conditions on the site, and so that they did not disrupt ongoing activities, many aspects of the site had to be considered. The information collation exercise therefore resulted in the collecting together of information that was represented in many different media, and held by several individuals. The information collation phase involved bringing together this apparently disorganised set of represented information into a unified structure, the output of which would form the basic problem specification forming the input of the next design phase (the generation of a structural design).

The processes of information collation involved bringing together information relating to a particular design problem from the information gathering phase, and informed by this, producing a structured set of more explicitly specified knowledge that could be used as a means of specifying requirements for the development of new temporary works schemes. The information gathered by the construction team workers in the course of their involvement in the day to day running of the site in the information gathering phase was collected in a way that made sense to individuals who were using it on a day to day basis. The information was often represented in a media that was generated to aid the individual in their own activities, rather than as a component of a collaborative process for future design. Thus, scaffolders would carry sketchpads of scaffolding configurations; carpenters carried tables of woodwork measurements; and engineers carried various schedules, drawings, sketches, tables and notes, relating to work completed, work about to begin, and work underway. Some of this information was held mentally and these internal representations were not be directly accessible. To begin to collate this information into a unified state, the participants would have to communicate with each other to bring this privately held information into a publicly accessible arena.

Co-ordinating the information distributed between the participants was facilitated by the situated aspects of the construction activity, where the environment of the construction site and satellite office provided both resources and constraints to support this. The actual processes used by the participants to co-ordinate their understandings about design problems on the site, occurred through both direct and indirect communicative events. Direct communication involved activity that was primarily intended for communication, whilst indirect communication included activities that were not primarily communicative in their intent, although they had a secondary function as such.

**Direct communication**

Direct communication included reporting of events observed and of events that were expected. This took place in the weekly team meetings, but also in ad hoc meetings, and chance encounters, as people found themselves adjacent to a person who might need to know some information that they were party to. Team meetings were held at a specific time each week, chaired by the team leader, and all gangers, foremen, engineers and quantity surveyors were invited. An agenda was set (although not always followed) and all members of the team were invited to participate in saying what they had been doing, and whether there had been any problems on the site. At the end of the meeting the weekly work schedule would be handed out by the senior engineer, which the team were asked to comment upon.

A formal communication mechanism about activity on the site was the site record: at the end of each day, these were filled in by the engineers (on a pro-forma sheet), collected together, and filed, providing a common resource for all of the team to examine. In addition to acting as a resource for the team, copies were taken and passed to the main site office, where they were forwarded to the TWC and TWD, the resident engineer and the stakeholders affected. The site record provided a means of 'covering the teams backs', so they could not be accused of failing to notice design-critical information, an important consideration in a traditionally litigious industry.

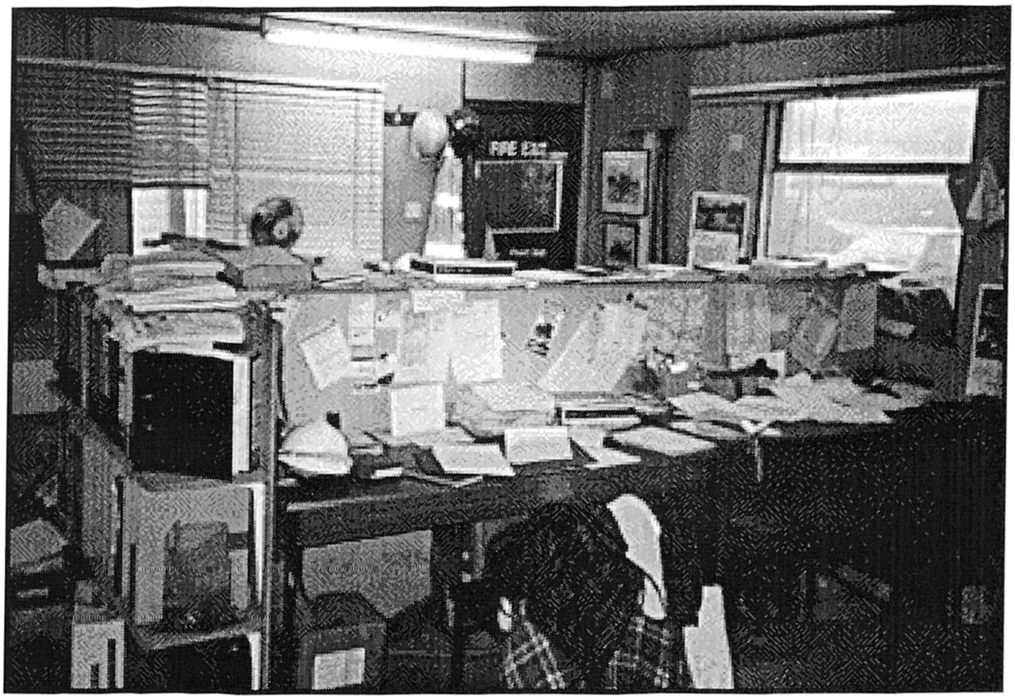
Another form of direct communication included the team members writing notes to each other, which tended to be used with single pieces of general information, or in asking simple questions; anything more complex would be left until a face-to-face meeting could be arranged. An example of this was observed in the sketch of gradients made in the information gathering phase: the graduate engineer left the sketch on the senior engineers desk, with a note attached to it explaining that he had found a discrepancy between the expected and actual gradient. It further commented that he was going to be away from his desk for the rest of the day, but informed the SE that he would be working at a particular location if he needed further information.

**Indirect communication**

In indirect communication, the context of the activity provided a mechanism for the transmission of information between people sharing that space. The physical structure of the satellite office allowed the behaviours of the construction team to be organised and to facilitate ad hoc communication, in a way that would not have always been possible under different environmental conditions.

The office was 'open plan', and the engineers and quantity surveyors therefore were able to see when other people were present, to speak to them without having to move from their desks, to overhear them on the telephone or when speaking to each other, and to see the information laid out on each others desks. There was a relaxed atmosphere to interactions, and when members of the team were not doing any work, they would engage in social conversations, or join conversations if something interested them[2]. These conversations almost always turned to work, and there was a constant stream of people coming into the office and asking for information. To demonstrate the resources available to communication, a photograph of the layout of the office is shown in fig. A.5.

fig. A.5. Photograph of construction team office.

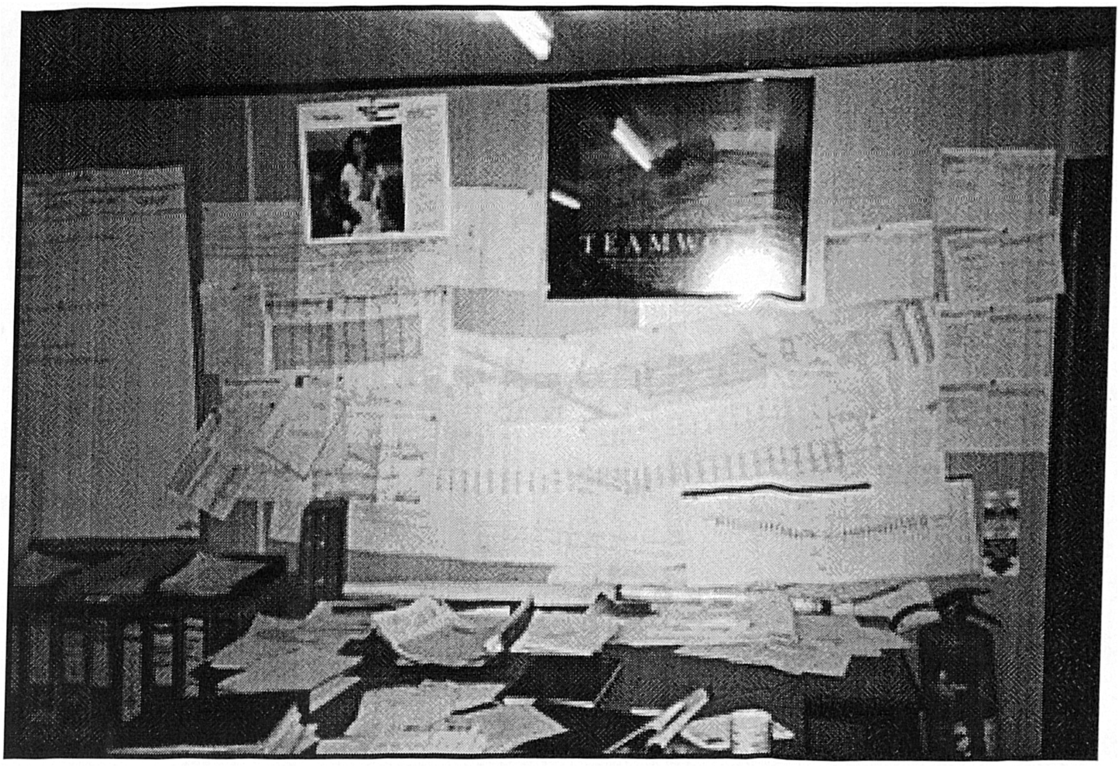


[2] These conversations were noticeably not joined by the labour or gangers, possibly due to social class boundaries, or due to a distinction between 'the management' and 'the workers'. This was reinforced in the way that the labour force did not have desks in the office, spending their working hours on the site. This was a *hierarchical* barrier to communication, although at the same time it provided an information filter for the engineers, reducing the volume of material that they had to be sensitive to.

As can be observed, the workplace was covered with paper and other sources of information. Paper covered almost every surface, often several layers deep, and frequently referred to material was pinned up on the walls. When information was required from a person who was not physically present, this 'desk litter' could provide clues to their location, in the forms of the drawings and other representations on the desk, as well as the task that they were currently engaged in. Other artefacts also provided information about the whereabouts of people: if a person's Wellington boots and hard hat were missing, they were probably out on site; if someone had a pair of muddy boots under their desk, it meant that they had been on the site and could be asked about the current work situation. Depending on the weather, it was even possible to see how long ago a person had been out on the site, for example from the wet or dried mud on boots, which could be useful if one of the team was trying to locate another individual out on the site. Other tools, such as the geodometer were also useful in this way - if they were missing from the office, then a graduate engineer would be out on site (in a predetermined location) and could be asked to run a favour by the more senior engineers. Even the window was used to see whether people's cars were in the car park outside the office (seen through the window in fig. A.5.): if this was the case, then that person was highly likely to be somewhere on the site.

The walls of the office, and in particular the partitions, were covered in pinned up artefacts, including permanent and temporary works drawings, sketches, time-space scheduling charts, calculations, photographs, calendars, information tables, the addresses of suppliers and subcontractors and other information deemed relevant. The senior engineer had a particularly prominent pinboard on the wall in front of his desk (see Fig. 11.) Of particular note on this was a calendar with various dates highlighted and circled, including bank holidays, and a drawing showing the positions of piles with the areas that were completed highlighted in fluorescent pen. A plan view of the road that was intended to go over the piles was pinned above the piling drawing, with measurements to the same scale These three representations allowed direct comparisons to be made between calendar information, piling work and the location of the piling work. This linked resources, spatial information and planned activity for the tasks involved in piling. Present and recently completed weekly work schedules were also pinned up, some with comments annotated on them, as to when the work had been completed, or problems arising from their construction. Sketches and amended drawings were also pinned to the board.

fig. A.6. Photograph of drawings pinned to senior engineer's wall.



Over the period of the fieldwork, the content of the board was changed by the senior engineer, some artefacts being removed and replaced (such as the amended drawings and weekly work schedules), whilst the content of others changed, such as the drawing of the piles, so that after each successful concrete pour, as piles were covered over, the pile locations were filled in with fluorescent ink to demonstrate the changes. These commonly accessible artefacts provided a simple visual representation of the state of the construction site (to those who could read the representation), and which could be directly compared to the project schedules.

One of the ways that knowledge was passed around the group was through asking questions; this might be a direct question to a particular person, or a general question, shouted out so that anyone in the room with the answer might answer. These questions usually were simple, and once the answer was given, the conversation was terminated. Spoken communication was conducted from the desks, allowing all of the participants in the room to be aware of developments, or allowing them to contribute to the discussion. When the senior or site engineers wanted to speak to the graduate engineers, they would stand up and chat over the tops of the partitions, providing a visual and auditory focus of attention in the room. This allowed people to work whilst keeping an ear to the conversation, keeping abreast of developments, to ask questions, and to add to the discussion. An example of this is noted below:

```
Senior engineer: <goes over to graduate engineer at his desk> 'Have
you got the delivery tickets for fifty two fifty six?' [the term
relates to a particular set of substructure pile reference numbers].
```

```
Graduate Engineer: <mumbles. Begins to search through a file on his desk>.

Quantity surveyor: <sitting on desk opposite graduate engineer, and overhears conversation> 'I've got copies. I think I've got the ones you're looking for'.
```

In addition to these 'open' conversations, telephone conversations were carried out in loud voices; this was partly because the level of ambient noise in the room could be fairly high, but also because it allowed the others in the room to overhear (one side of) the conversation. One of the site engineers in particular would deliberately raise his voice whenever he was speaking about topics that he perceived to be particularly pertinent to the others, even standing up and waving his arms around to gain attention, or pointing to artefacts that were relevant to the discussion so that the others in the room might get an idea of the topic of conversation.

The participants in the information collation phase were centred in the satellite office, but in reality spent large components of the time on the site, with the more junior personnel spending almost all of their time outside, working on the site, whilst the more senior team members (and the quantity surveyors) were only away from their desks for a short time over the day. Contact between the dispersed team members with the site which was some distance from the satellite office was made possible through the use of a portable hand-held radio link, which allowed the engineers and gangers or foremen to communicate with each other (eight radios were shared by the team). These radios were kept on all of the time so that contact calls could be made. The background noise of the radios was also used as a means of indirectly monitoring general activity on the site.

The almost constant babble of the radios in the office meant that distant radio conversations could be attended to. This was possible because of one of the qualities of the radio as a medium of communication. The radios, unlike the telephone, were set to an open channel: all communication took place on a common wavelength, so that both sides of a communication could be overheard by non-participants with access to a radio. As with an open plan office, which allows overhearing, or 'surreptitious monitoring' of conversations, the radios had a similar function for spatially distributed individuals. This demonstrates how a communications technology can enhance task performance when it conforms with, and meets the requirements of work practice.

At various points in day, it was common practice for the foremen and engineers to gather in the office at lunch, the beginning, and end of the day to discuss any areas that they felt were important. This time sensitive co-location was important for the propagation of information between the team members, because at other times, it was difficult to predict where particular people would be; at this time however, they were likely to be present in the office.

The culmination of the information collation activity resulted in the generation by the senior engineer of a new document called the 'design brief' or the TW2 (the temporary works specification). According to the ORGANISATIONAL procedures, the TW2 should be presented ten to twenty days in advance of the date required, depending on the complexity of the design problem. The construction teams were encouraged to include in this suggestions for the design, and the materials that they proposed to use, some of which they might already have, and which might prove cheaper than buying in resources from off-site. The TW2 often included a sketch of the site to represent spatial relationships, taking information directly from the senior engineer's own site visits or understanding of the problem, or through the re-representation of a sketch generated by one of the other engineers (such as the problem of misplaced piles noted above). Once the TWC had studied the design brief and discussed it with the team, the TW2 would be sent to the main engineering office.

In addition to generating the TW2, a great deal more information about the expected design was held in the head of the senior engineer that he did not believe appropriate to put in the TW2 for various reasons, including time restrictions, relevance, or even office politics (such as him not wanting the true cost of the temporary works to be available to his own superiors).

### A.3.3 Generation of Structural Designs

**Clarifying the design specifications**

The initial inputs to the structural design phase were the outputs of the information collation phase. However, because more participants become involved in to the design process in this phase, several new inputs must also be considered. These include general knowledge about the site known by the temporary works co-ordinator (TWC), generic knowledge about temporary works design processes and the permanent works designs known by the TWC and temporary works designer (TWD). The TWD also had access to previously created designs which could be re-used with little additional work on them. Additional inputs in the form of constraints on the temporary works design from agents external to ConsCo also have to be considered. These ranged from the resident engineer's knowledge about information relevant to the site, supplier knowledge about the performance of their materials, and other stakeholder knowledge (by the environmental agency and railway operator) about permissible designs. Constraints imposed by pre-existing documentation relating to legal responsibilities and national and international standards relevant to the construction and design process also have to be considered as an input to the process.

In the construction quality control documentation of the official ORGANISATIONAL procedures, the TW2 should be presented as a formal transition of a design representation to the TWC by the team's senior engineer. In practice, the TW2 was often little more than a few ideas sketched or jotted onto a scrap sheet of paper, because the senior engineer had little too time to perform the task, and often very little understanding of what information the TWD might require in the problem specification. Through discussions with the TWC, a detailed specification would be generated, containing information about the site conditions, the materials, labour and other resources available to construct the temporary works structure. Such meetings were usually booked on the telephone between the construction team's senior engineer and TWC, who would then sit down at the TWC's desk in the main site office, and pore over the permanent works drawings, the initial TW2 and several sheets of blank paper. As they discussed the problem, both tended to make sketches; often they elaborated on old sketches, jotting notes onto the sketch, and referring to features of the drawings by pointing at them. This could be seen in an example, where part of an interaction went as follows:

| |
|---|
| Senior engineer (SE): 'If you look here, there's a barrel run there' <points at sketch generated in the meeting of a section view through a design structure> |
| Temporary works co-ordinator (TWC): 'Yes I see'. |
| SE: 'So if we dig here...' <he holds one hand to the sketch and runs a finger on the other hand along a permanent works drawing (plan view) beside the sketch, indicating a line of reference> |
| TWC: 'No you can't do that because of drainage problems...' <pauses> '...No, no, I see now'. |
| SE: 'So if we cap these piles here...' <indicates several points on the sketch> |
| TWC: 'Yeah. OK. Lets do that'. |

The discussion also demonstrates how a common understanding of the problem was generated through cross-referencing different representational forms. Here, the senior engineer mediated the co-ordination of two representations on different artefacts by using his hands to demonstrate the spatial relationship between the drawing and the sketch, holding one hand to the relevant location on the sketch and the other, running along the permanent works drawing to indicate where the digging on the sketch (the section view) would have to be performed over the drawing (the plan view). This allowed the information on one representation to be mapped onto another to generate a third, processed representation.

The time spent on developing the TW2 was determined by the complexity of the design problem; this could range from a few minutes to several hours, and on occasions, involved multiple meetings. During meetings in the TWC's office, the other production support team members could overhear the discussions and occasionally provided information relating to the schedule and the availability of temporary works supplies (their specialist areas) that affected the design problem being discussed. When problems arose with deciding on the specifications or on the possible configurations of the design, the TWC would often break off the meeting to make a telephone call to someone who might know the answer, continuing the meeting when furnished with the necessary information.

The end result of the initial meeting or meetings between the TWC and senior engineer would result in the creation of a 'final TW2' by the TWC. The TW2 was intended to be a precise and consistent indication of the problem, discussed in terms of site specific information, the problem encountered, and the resources available. In theory, the TW2 should contain all of the information the temporary works designer would require to solve the problem situation. The TW2 would be filled onto an official form, appended with any sketches that were needed to unambiguously describe spatial relationships between objects, and copied, one copy sent to the TWD, one retained by the TWC, one by the construction team, and one sent to the project manager to add to the dayfile. The TW2 was therefore the first unified representation of the temporary works design problem.

**Specification and structural design**

The next stage in the structural design process involved the TWC contacting the temporary works designer (TWD) and passing on the TW2 to them. The task of the TWD was to transform the specified problem, made up of the conditions of the site and the resources available, into a design solution matching the requirements of the design brief. The work of the TWD involved reading the literature on standards, working on calculations, or drafting the drawings and sketches by hand on drafting tables. In addition to this, the TWD had to generate method statements of how the structure was to be erected, and risk assessments on the most dangerous aspects of the erecting the construction.

Often, the work of the TWD involved calculating the stresses placed on an existing structure to see if it was strong enough to cope with the expected loads (including an adequate safety factor). Occasionally, the TWD would simply be asked to approve whether a certain plan should be allowed to go ahead, although more frequently, they needed to enter into complex discussions with the construction team to coax out their requirements more clearly. The work involved in generating structural designs also involved checking that the new designs matched the requirements of the other stakeholders.

Co-ordinating the design of temporary works structures between the expectations of the team and the understanding of the design problems by the TWD was conducted by the TWC, who acted as a go-between, conducting a 'diplomatic' service between the construction team and the temporary works designer. The work of co-ordination by the TWC often entailed long telephone calls between the site and the TWD, including the faxing of tables, sketches and preliminary drawings (shrunk with a photocopier) to the TWD. This was intended to improve the design of the temporary works, matching them to the specifications set by the team - implicit and explicit.

The design brief (TW2) generally represented the problems faced in a sketch form. This was often annotated, and followed by a brief (text) explanation describing the problem, the resources available to solve the problem, the constraints on the possible activities that they could perform, and when the design would be required. Communications between the TWC and TWD following this initial contact generally took the form of annotated sketches faxed between the TWC and teams. The preliminary designs involved the generation of engineering drawings or sketches, drafted out by hand and sent to the TWC. Graphical representations were crucial to the work of the TWD because they were typically the form of information that they initially received on the design problem. They also used them to communicate with, as well as the media that they worked on. Sketches were important in communication, because of the difficulty in verbally and textually communicating spatial information, or the relationships between objects. However, a problem with faxing sketches was that the quality was extremely variable, and blurring occasionally obscured features that had to be clarified in a further exchange.

Whilst the role of the temporary works co-ordinator was to improve communications between the designer and the construction team by mediating between them, there were also disadvantages. One of these disadvantages was that the TWC became another obstacle through which communication had to move, with the potential of slowing down the process and filtering out possibly valuable design related information.

The design work in this phase was highly organised and regulated: sketches and drawings were all given reference numbers and as they progressed from specification to verification, they underwent a rigorous process of checking and counter checking. At each stage of this process, the drawings were marked, either with a stamp ('preliminary', 'for discussion', 'for inspection', 'for construction'), or with a signature to demonstrate that calculations on the aspects of safety tolerances for the drawings had been checked. Red ink was used on the stamp so that unauthorised copying would not result in 'uncontrolled' drawings (the duplication process resulting in all black copies) and meant that it was possible to tell which drawings were originals. This was important to the design processes, because amendments made to multiple copies of drawings were difficult to keep track of, and could potentially result in the construction of defective designs.

**Stakeholder involvement**

Temporary works design meetings, including the TWD, the TWC and the team leader, the site and senior team engineers were usually held on a two weekly bases to discuss the team's response to the preliminary sketched out design ideas and drawings submitted by the TWD in response to the design brief. These meetings allowed the team members to make face-to-face contact with the TWD to match their understandings of the problem to the design solution reified in the drawing. In most meetings, heated exchanges were observed as the team challenged the TWDs understanding of the constraints imposed by the physical characteristics and available resources on the site. The TWC was required to act as a buffer in these cases due to the acrimonious and personal nature of some of these interactions, the construction team members complaining that the TWD has misunderstood their specifications, and the TWD claiming that he was not made aware of all aspects of the problem by the team in the design brief. Such meetings resulted in a set of minutes, detailing the comments made by the team and the TWD, written up by the TWC, and detailing the changes that needed to be made to the preliminary drawing, and additional information that the team had to make available to the TWD in order to make the required changes. These initial discussions would result in the creation of the second generation of (still preliminary) temporary works drawings. These were stamped with the words 'for discussion' and were not allowed to be used in construction.

Design meetings with the RE were held on a two weekly basis alternating with the temporary works design meeting. These involved the presentation of the drawings to the RE (those stamped 'for discussion'). Occasionally, these meetings might result in the RE demanding changes to the drawings. Requests for redesign would involve a breakdown of the reasons for rejection, noted in the minutes and passed to the TWD. Meetings with the other stakeholders were also held on a monthly basis. The drawings also had to be 'passed' by the other stakeholders: the environmental agency was worried that chemicals would leak into the water table if certain construction techniques were not used, and they had the legal right to request change or even complete redesign of the temporary works drawings if there was a danger from pollution. The railway operating ORGANISATION was also worried that the temporary works over the railway lines would allow concrete or other materials to fall onto the lines causing an obstruction. The railway operator had ownership over the land affected and therefore had the right to demand changes in the temporary works designs if they felt that this was not being attended to. Following these consultations, and their resolution, alterations would be made to the drawings if necessary, and the would be stamped with 'for inspection'.

In all cases of meetings, minutes would be taken by the TWC, placed in the project dayfile and circulated. All correspondence relating to the design from the construction team, the RE, suppliers, subcontractors and internal communications were also placed in the dayfile. The dayfile was forwarded to the TWD, so that they could become aware of the local circumstances surrounding the project. This was intended to make the agendas of the stakeholders more obvious to the designers who were physically distant from conditions on the site, so that implicit knowledge might be better understood by them.

The last part of the process through which the structural design drawings would have to pass involved a senior engineer who was independent from the design process. The independent engineer checked through the 'for inspection' drawings and calculations for accuracy and other potential difficulties. If no problems were discovered with them, the drawings were 'signed-off' with a signature on the drawing and passed on to the site document control office. The final output of the structural design phase in the design of temporary works was therefore a drawing, and marked with a 'for construction' stamp.

The final drawings were logged at the document control office, who entered them into the 'drawing register', a list of all drawings on the project. The document control office maintained the original copies of the drawings so that duplicates were not circulated. All of the drawings in current circulation to construction teams were noted, so that the people in possession a drawings could be contacted if amendments were made to them. Documentation relating to drawings amendments were held on computer, so that all of the correspondence from the dayfile relating to those drawings could be called up quickly[3].

The structural design phase therefore involved the collection of requirements from the construction team, the production of draft copies of a proposed design, checking that the requirements of the various parties involved were met, generating a final design for use in construction, and transmission of the drawing to the construction team. Whilst one person (the TWD) was involved physically transforming the temporary

[3] Although important in the design of the drawings, calculations were not generally sent out with the drawings to the site, because they were represented in the structure of the drawings themselves.

works problem into a design solution, the specifications and determination of constraints on the design itself was highly collaborative.

Other outputs from the structural design phase included 'knowledge in the head' of the team's senior engineer about applying this information, derived through discussions with the TWC, TWD, RE and other stakeholders. This knowledge included information about the drawings that was not explicitly represented in the drawing, such as how best to lay the concrete: this could be done from side to side across the road, or lengthways, along the direction of the road, each of which had different loading characteristics. Other information was available in the method statements and risk analyses prepared by the TWD. These accompanied the drawings to the document control office and were logged onto the computer database so that they could be cross-referenced to the drawing. The method statements and risk analyses were distributed to the team with the drawings when requested.

### A.3.4 Organisation of Site Activities

Once the temporary works drawings had been signed off and distributed, the construction team had to plan how they were to proceed with erecting the physical temporary works structures. The inputs to the process were essentially abstract representations of form, made up of lines representing structural forms. The T/W drawings were supported with material in the margins of the drawings summarising information about the design (such as amendments), and the method statements and risk assessments.

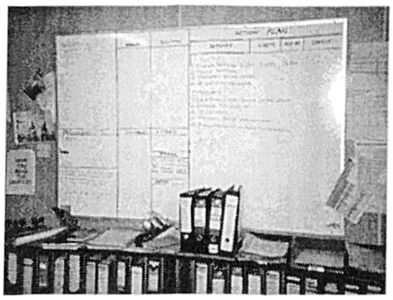
Other inputs to the phase consisted of the internalised knowledge of the senior engineer, along with the stage programme (the three monthly schedule of the team's construction activities). This activity planning phase was not a trivial process of following instructions laid out by the TWD in the temporary works drawings, because construction resources had to be organised, including the ordering of materials and plant, breaking the drawings into activities that could be performed by the individual teams members, and determining the order of erecting the materials described in the drawings.

The organisation of the office was a major factor of how the engineers quantity surveyors and foremen interacted with one another, because it determined access to other people and the artefacts used in the co-ordination of work activities. Many of the activities that were planned had been performed before, and could simply be repeated, with minor alterations. When these activities had been performed by other people, this information was available either by asking other people in the office (it might even be volunteered by the person delegating the work), or through searching through the team's project filing archive. Project related information was contained in the many files scattered around the office and stored in files indexed by task and by date. Individuals also maintained their own files of activities that they had been involved with, which could provide information when they were not present in the office.

One of the mechanisms used by the senior engineer and team leader to allocate work and to inform the team members of planned site activities was through the use of a whiteboard (see photograph in fig. A.7.), on which several permanently marked out sections headings were written on it. The whiteboard provided a means of asynchronous, one to many, communication between the people in the office. Things written on the whiteboard allowed the workers in the office to see what the plans were and to write up comments on the board. In general it was written onto mostly by the team leader and senior engineer, and rarely by the others, who usually just read the details. Information on the board provided a means of making people aware of planning activities and things that had not yet occurred, and which might not be readily apparent from the other resources in the room, many of which only afforded awareness of things currently operating, or had already happened.

| Meeting | Problem | Solution | Action Plan | | | |
|---|---|---|---|---|---|---|
| | | | Activity | Whom | Due By | Status |
| Deliveries | Bulk Material | Visitors | | | | |
| Team Meetings | | Training | | | | |
| | | Meetings | | | | |

fig. A.7. Photograph of whiteboard in construction team office.



The senior engineer initially worked alone on the drawings, allocating responsibilities amongst the site engineers, who in turn delegated tasks to the graduate engineers. It was important that certain tasks were completed in a particular order, so that for example, plant was moved before the bridge deck scaffolding was erected. If this was mis-engineered, large machinery could be trapped by the scaffolding until it was 'struck down' (removed by the scaffolders), resulting in increased hire costs, or delays to other areas of the construction. Attempts were made to determine the 'critical path' of the construction work, which involved planning the design areas that were central to completion of the project on schedule. Delays to these 'critical' areas would result in a slow-down of the construction work. Determining the critical path of the team's activities was therefore seen as a vital component in the organisation of the team's activity.

The physical state of the site, including the weather, soil structure, positions and form of the existing structures were a guiding feature on the possible ways that the resources could be organised to construct the temporary works. The context of the site therefore provided constraints to the types of operations that could be performed, limiting the possibilities for action. Organisational constraints also operated: for example, whilst the construction team worked on weekends, few subcontractors or suppliers did. This meant that activities requiring the participation of these groups had to occur on weekdays, and tasks had to be allocated so that some types of work did not fall onto weekends. The range of activities that could be planned was therefore limited, and whilst there might be many theoretical ways that structures might be erected, in practice, these were reduced by practical circumstances.

Information on the form of the structure derived from the drawings would be supplemented with information about when to build it from the stage programme. The stage programme was broken down into a weekly schedule by the senior engineer and team leader detailing the sequence of the activities to be performed by individuals. This schedule broke down the week ahead into activities, assigning responsibilities for actions to particular gangers and foremen. This was performed in advance of the team's activities, but was regularly updated to incorporate changes arising from the delays and (occasional) activities performed ahead of schedule.

The weekly schedule was handed out and discussed with the team at the weekly team meetings, involving the team leader, engineers, quantity surveyors, foremen and gangers. These team meetings would begin with the team leader updating the team on how they were performing against the schedule on a long range forecast. Photocopies of this information would be handed around, and the team would be asked for comments and suggestions on improving performance. Foremen and gangers often made suggestions about how to allocate the labour to best perform the tasks assigned, and how problems with obtaining plant and materials might slow down construction. Alternatives were discussed and these noted by the team leader and senior engineer in their personal logbooks. Amended weekly schedules would be placed on people's desks when suggestions were taken up and changes made.

Artefacts used in organising the activities on the site included sketches and tables, which were used to transform information from the drawings into simpler representations. The simpler representations were specific to particular forms of use, such as tables of locations on where to erect the temporary works materials. These were also shown to other people to help describe what was required more clearly than could be done using language or by showing them the original drawing. An example of this was the sketches used in erecting scaffolding which were handed out to the scaffolders by the engineers. These sketches showed only the positions of the scaffolding and the ways in which the struts were to be joined together; they did not carry information about loading weights or their eventual function, which was not important to the scaffolders. Another property of different representational forms was that they allowed a time dimension to be incorporated into the representation, such as tables of when work was to be performed, or more simply, through omission, in sketches that did not include design information that would be required at a later date.

For all of the construction activities planned, a detailed method statement had to be prepared describing the work procedures undertaken by the labour. This was performed by the site engineers for the features assigned to them by the senior engineer. In parallel to this, risk assessments of the dangers imposed by the method had to be generated. These determined where the work was potentially dangerous and was used to alter the method statements so that the risks would be minimised. For example, using ladders incurred a high risk of causing a fall as the ladder toppled; this could be minimised by either tying the top of the ladder to the structure, of by having another person manning the base of the ladder. These method statements and risk assessments were similar to those produced by the TWD, but were at a much lower level of detail (physical actions), whereas those generated by the TWD attended to more abstract levels of activity, such as designing structures minimising the need to climb ladders in the first place. The site engineers reported that the TWD's method and risk documents were used as a attention raising resource, because they showed where more work needed to be done. All method statements and risk assessments were filed for later use and legal reasons.

The outputs of the organisation of site activities phase resulted in the production of detailed instructions that would enable the co-ordination of resources necessary to build the temporary works structures. These included written (the weekly work schedule), sketched and verbal instructions of work to be performed by the labour. These were given to gangers and foremen in the team meetings and ad hoc meetings. Other forms of instruction re-represented information in the drawings into tables of measurement for construction (and subsequent checking), developed by the graduate and site engineers themselves from the drawings. Reminders of instructions about the procedures and other related information were written onto the whiteboard. The order of things which were to be performed, and by whom, were recorded on the weekly work schedule and distributed. The method statements produced by the site engineers were distributed to the gangers and foremen who would use them to direct the physical work of constructing the temporary works structures on the site during the construction phase.

### A.3.5 Construction

The construction process took as its inputs the outputs from the previous section which was incorporated with the tradesmen, gangers and foremen's knowledge about general temporary works construction technique. The process was initiated by the graduate engineers, who took measurements with the geodometers and theodolites to ensure that the temporary works materials were placed in the correct locations; the foremen then took over and unless problems developed, the engineers were not involved in the construction phase from this point.

The initiation of subsequent activities was derived from the weekly work schedule, work being undertaken on the scheduled date (all else going to plan, which was not always the case). The engineer's and foremen's sketches and the method statements were used as guides in the erection of materials by the carpenters, who built the concrete moulds, and by the scaffolders, who erected the scaffolding towers around the bridge deck.

The foremen spent much of their time on the site visiting the areas of activity and making sure that the temporary works were being constructed according to the drawings. The gangers worked closely with the crafts people on the site and were able to manage the work on a moment-by-moment basis. The gangers and foremen used their radios so that they could ask each other questions, requisition materials, or locate people around the site. If problems developed on site, the gangers and foremen could radio the office to ask for assistance from engineers there, or they could drive their four wheel drive vehicles back to the office to engage in face-to-face meetings.

The distributed nature of the site made contacting individuals difficult. When people were not present to talk to directly, other media were used to communicate, either through the use of the radio link, through placing written notes, sketches, method statements or risk assessments on people's desks, or jotting notes onto the whiteboard. Messages were also left with people who were in the office for when the person came back. An example of how one such person-location was performed using a radio is shown below. Note how the participants recognise the problem and pre-empt a request for them to pass a message on:

```
Site engineer: <Radioing from site office to the site> '15 to 17. Come in.'
Foreman: 'What you want?'
Site engineer: 'Have you seen Florida Phil?'
Foreman: 'Hello? Having trouble receiving you.'
```

```
Site engineer: <repeats slowly> 'Have you seen Florida Phil?'
Foreman: 'Nah mate. He was here earlier.'
Site engineer: 'OK then. See ya later.'
Foreman: 'I can get him to call you if I see him'
Site engineer: 'You do that. Ta mate.'
```

The outputs of the construction phase included the constructed temporary works structures, including features such as aerial walkways, concrete moulds, scaffolding for concrete mould supports and so on. To demonstrate that the work had been performed, the weekly work schedule was marked as 'completed' and handed to the senior engineer, who in turn informed the team leader. To make this more generally known by the team, the whiteboard was updated with this information.

### A.3.6 Reporting

The reporting phase was essential to check that the designs had been implemented correctly, so that they were safe to use, and matched the contractual requirements of the client. This involved examining the built temporary works structures, and comparing them to the drawings. Various people and ORGANISATIONS were involved in this phase, and the work ranged from simple visual inspections of the work to precise measurements with geotechnical equipment. This redundancy of checking was important in ensuring that the design was constructed correctly - bridge failure, as well as being expensive to repair, could result in injury or death, and the penalties for such failure could be severe.

The team attempted to maintain strict controls on the construction of the temporary works because any discrepancies that were found after construction could result in remedial work having to be performed, which would be both costly and potentially damaging to ConsCo's reputation. The work performed by the team involved examining the temporary works structures being built and the methods used in constructing them. The engineers continuously checked work as it was being conducted, by taking measurements of the positions of the built structures (with geodometers and theodolites) and comparing these measurements to the expected dimensions of the temporary works designed forms. Rather than taking the complete sets of drawings onto the site, measurements were often taken from the drawings and turned into tables of figures which were easier to read and carry about on the site. Whilst the engineers were involved in this measuring process, they, along with the foremen, checked on the methods used by the crafts people, and compared these against the method statements prepared earlier. The gangers also used their prior experience of construction activities to check on the methods used.

In addition to the team themselves monitoring construction, the project contract between the resident engineer and ConsCo involved a formal aspect to the reporting process, in which the RE checked the structures to see that they had been constructed to the contractually specified level of quality. This was either performed by the clerk of works, who continuously patrolled the site, or by the assistant section RE who would be called on site to examine the more complex or critical aspects of work. As each structure was completed, the graduate engineers would have to ensure that a form was signed by the assistant section RE (known as 'clause 17s' and 'clause 38s'), agreeing that the work had been performed to the appropriate standard. This form was copied and sent to the RE, the site main office for inclusion into the dayfile; one copy was retained by the team.

Other ORGANISATIONS were also involved in checking operations on the site to ensure that the work did not disadvantageously impact upon their operational areas. The railway operating ORGANISATION needed to check that the structural work did not represent a hazard to their train services on the railway line, and the environmental ORGANISATION had to ensure that work did not result in environmental damage or pollution to the watercourses. In any instances of failure to follow previously agreed upon methods, they were able to demand a halt to work until the situation was resolved with a redesign or change to the construction process.

An example of such a problem observed in the fieldwork was observed that demonstrates the importance of following the designs, and where reporting on progress was a vital component of the construction work:

> On one occasion, the team's carpenters had run out of planks to build a supporting platform over the bridge. They did however, have thicker planks available. Rather than ask if these were usable, the craftsmen took the initiative, reasoning that the planks, being thicker, would be even safer than the originally designated materials, and they used these instead. However, this solution was not as simple as they had imagined: because the planks were thicker, they were also heavier, and placed a greater load on the structure. This was above its projected loading tolerance.
>
> When this was noticed in a routine check by staff from the railway operator, a formal complaint was made to the team leader, who decided to have the strain tolerances recalculated for the new materials. He communicated the complaint and the properties of the new material to the TWC; the TWC passed the problem on to the TWD, who calculated that the loading factor was dangerously high. This information was communicated back, and the structure had to taken down and rebuilt with different materials. This was heavily time-consuming, and because it fell across the critical path of the project, it delayed other aspects of the task and increased the overall expense of the construction work.

Whilst the drawings were used as the basis of activity, they were not usually compared directly with the built structures, except where the structure involved a simple visual comparison. Other representations than the drawings were used, including sketches and tables made by the engineers to take out onto site. These captured elements of the drawings, but meant that the whole drawing did not have to be taken with them because only the relevant information for a particular task was displayed on the artefact. An example of this can be seen in fig. A.5, where a graph of gradients was used so that distance could be plotted against height. Non-graphical representations were also used in checking and reporting activities: the works records (site 'diaries') were written by the engineers to document changes to the construction requested by the resident engineer, and on the completion of work activities, or as requests for further information about the design from the site office. These works records formed a valuable source of information about the current state of the site to the senior site management. The site records were placed in the project dayfile, making the information available to all personnel involved with project. The site manager also forwarded the site records to the people that they affected in the project. Here, there is a 'chain of representations', propagating a representation from the site to other people who needed to be made aware of the state of the site, but were not in direct contact with the construction team.

The outputs of the reporting phase included the forms filled out and signed by the assistant section RE (clauses 17 and 38). Other outputs existed in the heads of the engineers, containing information of the state of the temporary works structures at a particular time and whether or not they were built according to the designs or had inconsistencies. The end product of the reporting process was a 'pass' or 'fail'. If the temporary works structure passed inspection, no further work would have to be performed, but if a fail was recorded, adjustments would have to be made to the structure. In the rare event of the discovery of major problems, failure would result in the design being resubmitted to the TWD, and the structural design, organisation of activity and reporting phases repeated.

An output that the team was intended to produce were 'as built' drawings, representing the structures that had been constructed. These were to note the actual configurations of the temporary works, noting in particular where differences to designed structures had occurred (a common feature of construction being that structures would be erected differently to the design, due to local conditions, materials available, or through minor error). These were intended be generated through taking measurements on the site and applying them to the original, 'for construction' drawing, rather than through creating a new drawing from scratch. However, no instances of preparing as built drawings were observed, the reason stated was that time limitations made the task impossible to perform, and that it was only for internal use within ConsCo (and was therefore an unnecessary procedure, because there were no legal or contractual obligations to do so). This meant that following the completion of the construction project, the only information that would exist about the process of construction would be the original drawings, the completed structure, the records available in the dayfile and knowledge about the construction by the personnel involved.

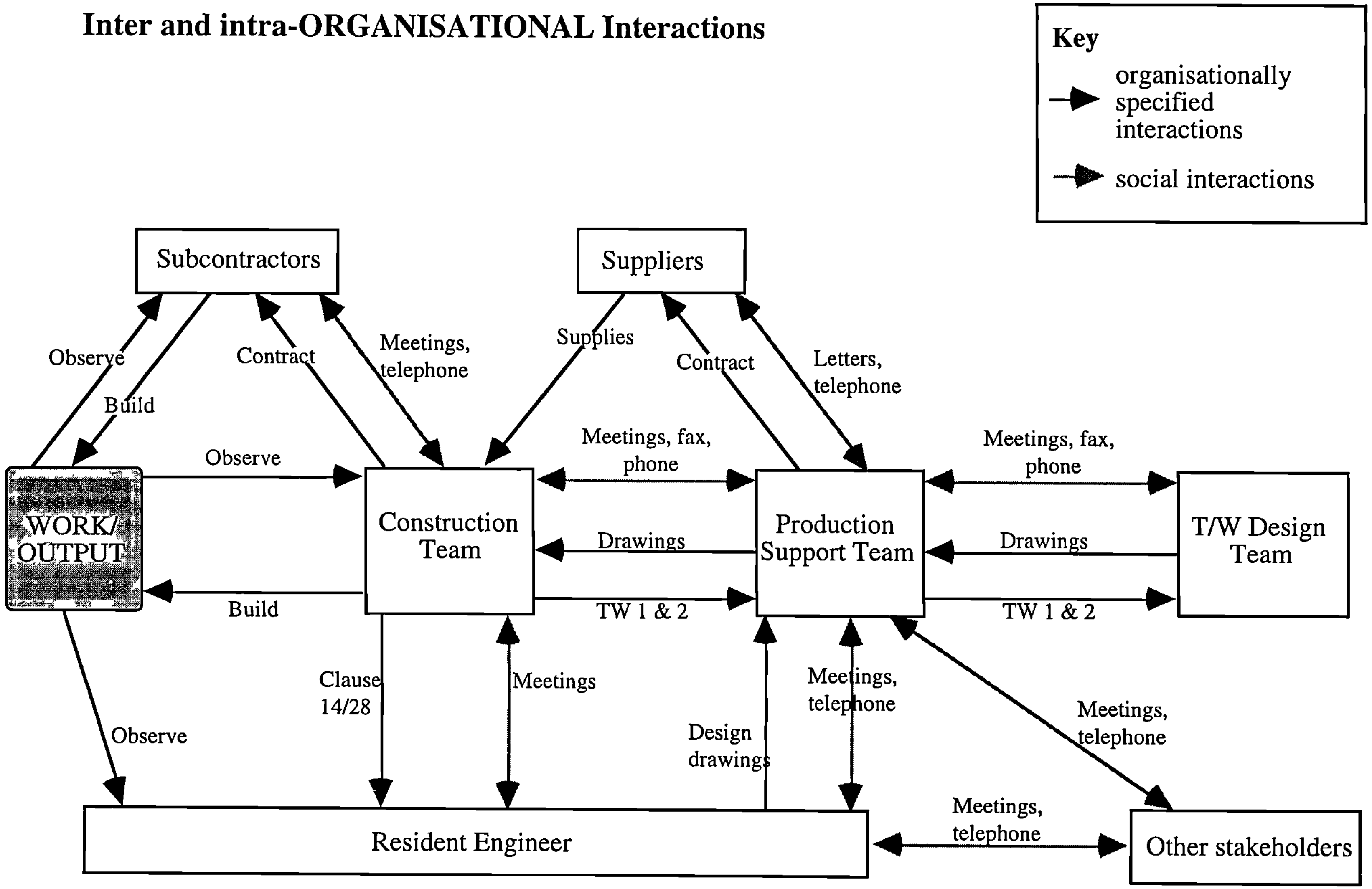
## A.4 Features of the design process

### A.4.1 Intra and inter-ORGANISATIONAL activity

Inter-ORGANISATIONAL activity in ConsCo was highly complex involving multiple people and laborious co-ordination activity. Design related activity was not limited to a single commercial entity and involved a number of stakeholder groups. This could be observed in the example described in A.3.6, involving the team's carpenters working with different plank sizes to those originally specified, so that other stakeholder bodies became involved. This demonstrates the importance of examining the *activity*, or high level task, as a unit of analysis, and not just the ORGANISATION. The interactions within, and between the ORGANISATIONS involved in the design of temporary works are shown in fig. A.8.

Fig. A8

## Inter and intra-ORGANISATIONAL Interactions



### A.4.2 Bi-directional movement of representations

The permanent works defined in the engineering designs for the construction site were largely pre-determined at the beginning of the project in the drawings generation by the Project Engineer, and in the tender application put forward by ConsCo. These contained the specifications on scheduling and building processes. However, not all of the details were pre-specified, and some design details were left to be determined at a later time.

Whilst the construction work stemmed *from* the drawings and schedule, in reality, design and project planning were also performed by the team at many levels. These included suggestions for changes to the high level design concept in the materials and processes of temporary works erection, down to the implementation details that were left unspecified, and interpreted 'on the ground' by team members. In effect, whilst the flow of communication was planned as a one way channel from the Project Engineer, broken down into more manageable and simpler components towards the labour force and construction work itself, feedback about the site, in the form of various kinds of representation, also had to flow back *up* the chain of command, from the construction workers, to the team's engineers and back to the Project Engineer, via the RE. Whilst movement of representations downwards towards the construction team was well specified by ConsCo's official procedures, the design related information circulating around the problems and conditions on the ground was less well specified.

Official procedures for the communication of information moving up the 'chain of command', from the implementors to the conceptual designers were arranged, involving meetings, but these were held relatively infrequently. Weekly internal team meetings were held, with other groups meeting on an even less regular basis (such as the inter-team, team-RE, team-environmental authority, and team-railway meetings). In addition to meetings, paper based forms were used to communicate construction problems around ConsCo and other ORGANISATIONS, and engineers were obliged to fill in 'works records', which were distributed with the dayfile. Most of these 'upward' communications were, however, informal, brief and opportunistically passed on using the resources closest to hand, on post-it notes, in telephone calls, or as verbal messages. It was the nature of these opportunistic communications that they were easily lost or misinterpreted: informants said that they forgot verbal messages; written notes were lost under other papers or passed on too late to be of use. Such communications were also potentially ambiguous: the informants noted that (indexical) terms such as 'it' or 'that' could be interpreted differently by conversationalists. Whilst these messages were quick to create, their information could be misused, demonstrating the fine line between the benefits of formality and the costs of an increased bureaucracy (Dahlbom and Mathiassen, 1993).

### A.4.3 Patterns of communication

Whilst the flow of representations down the ORGANISATIONAL hierarchy, from the Project Engineer to the labour force, was relatively simple in terms of its structure, complications could occur which forced information to move back up the hierarchy. In order to solve problems that arose, agents had to first contact the person that they saw as appropriate and then communicate this to them, describing the salient features and why they were a problem. In a spatially dispersed team, such contact was hard to achieve. As a consequence, messages were often left with other team members to pass on, notes left on desks, radio requests sent out, or they might actively search out that person. Once contacted, the problem had to be described unambiguously. How this was done was dependent on the complexity of the problem, ranging from the sizes of planks to be used in concrete moulding, to more complex matters where the RE had requested information about the concrete loading on the bridge substructures. Depending on the circumstances - the complexity of the problem and the background knowledge of the participants - a few words might suffice; in other situations, a longer meeting, involving protracted speech and involving the use of artefacts - charts, graphs, schedules or drawings - might be required to resolve the situation.

Construction operations were co-ordinated by the constant stream of artefacts between the participants to the activity. The structure of the communications involved in co-ordination was partly made explicit in ConsCo's 'Construction Quality Plan' which specified how, or in what order, actions were to be performed. Not all of the events that occurred on the site could be predicted in this quality plan, and these had to be managed on a case by case basis, relying on the team members' experience of similar situations and what behaviour they believed to be appropriate in such situations. Many of these situations were not demanding, involving simple requests for information or confirmations of work performed. However, this difference in the two forms of information, ORGANISATIONALLY structured and those developed in an interactional, ongoing basis, is important in understanding how the design system processed the information it needed to perform work.

ORGANISATIONALLY structured communication of design representations typically involved artefacts being transmitted to and from the site office, in various forms, and to and from the RE. This involved the transfer of design documents from one party to another, using particular, pre-defined channels which determined who should make and receive the information. The permanent and temporary works drawings were particularly highly controlled to avoid the construction of out of date drawings, which would necessitate redesign of other parts of the project or demolition.

The socially mediated communications were harder to follow in the fieldwork because they did not usually persist in the environment for long as a permanent physical record. These typically were involved in co-ordinating the use of, and creation of, the ORGANISATIONALLY structured representations, involving spontaneous social interactions and the use of opportunistic resources, such as pen and paper ('back of an envelope') sketches, scribbled notes on scraps of paper, or verbal queries yelled out across the office.

### A.4.4 Artefacts in the design process

The technologies for communication were numerous and diverse, including those explicitly recognised as communications technologies such as the telephone and fax, and those used as a means of communicating non-verbal information, such as the drawings and schedules. In addition to these methods of communication, the method statements, risk analyses, sketches, post-its, 'desk litter', speech (direct and overheard), the weekly work schedule, letters, works records (site instructions, site records and requests for information) and other paper based forms had to be completed in the course of work. All of these artefacts bore representations that could be communicated between the collaborating actors involved, allowing them to perform their own individual tasks as well as achieving the high level design goal.

The fieldwork demonstrates how the construction team stripped detail from the design artefacts, and added knowledge to these representations to create more succinct and modified representations. The new representations were better suited to their user's localised purposes. As these representations were propagated between people with different functions in the design process (determined by the division of labour), these artefacts assumed different purposes, and their representational status became altered. As representations were discarded or modified, their underlying informational content underwent change, and information processing occurred. At the end of a long chain of such transformations, the design representation had progressed from a definition of the problem into a solution for it.

### A.4.5 The allocation of tasks

The organisation of activities in ConsCo was loosely knit, relying on a 'just in time' management ethos; in reality, informants said that this translated into a fire-fighting mentality, where design information was often described as being delivered 'just too late', leading to delays in the critical path and the project running over time. The remarkable feature of the building site however, was that it operated despite this general disorder and lack of forward planning. Long range forward planning was not always possible because it was often difficult to identify problems in advance, and because team members had little time with which to generate detailed activity plans. Most of the observed activities were arranged 'on the fly', emphasising the contingent nature of collaborative planning, and the ad hoc methods used to achieve this co-ordination. An example of one such situation observed is given:

| |
|---|
| <Scene: A site engineer is on the telephone, speaking to a remote person and discussing a concrete pour. Only this part of the telephone conversation could be monitored by the fieldworker> |
| Site engineer: <stands up and speaks loudly into telephone> 'So, what I'm asking is: should we put concrete into the tower?' <raises his head and looks at the senior engineer with raised eyebrows> |
| Senior engineer: 'Yes'. |
| <Site engineer, completes the telephone call, then lifts a radio to speak to a foreman to give the go ahead. A graduate engineer overhears this:> |
| Graduate engineer: <orients towards senior engineer> 'Do you have any spare...<pause>...can I have three cubic metres?'. |
| Senior engineer: <Pauses. Looks at ceiling. Pushes tongue into side of mouth. Pauses. Looks at graduate engineer> 'OK. Yeah.' |
| <Site engineer overhears this and radios through to the foreman to arrange it>. |

In this observation, the potential to overhear telephone conversations (because of the open plan office space) is used by the site engineer as a means of asking the senior engineer if he can go ahead with construction. This was not pre-planned, but arose from a request for information arising from a distant third party. A graduate engineer, in turn, over hears this, and makes a request for materials, which was organised by the site engineer. None of this was prepared in advance, and the tasks were fluidly discussed and finalised as the participants were made aware of on-going activities around them, which they used to initiate and direct their own work.

Whilst allowing a high degree of autonomous freedom in behaviour, ConsCo operated within a central organisational framework that allowed the participants an understanding of the responsibilities and roles that each was expected to perform. Knowledge about how to operate within this framework was distributed across the Contract Quality Plan, the experience of the participants, and in the structure of the artefacts used in the construction process. These were often weaved together, where, for example, the quality plan would be used as a resource by an engineer who knew that under specific conditions, a particular procedure had to be followed. On following this procedure, an artefact would be created using the information from another artefact, whilst also drawing from their personal knowledge of the site. The structure of the created artefact would then determine how it would be used in the next stage in the design process - if it was paper based, it would have to be passed on physically, and would either require an accompanying letter explaining its purpose, or would be transmitted by hand. This was likely to result in conversation between the carrier of the representation and the recipient, explaining the reason for the document and might develop into a more general discussion covering other aspects of the construction work.

An example of this knowledge distribution occurred when a graduate engineer was asked to check on the particular characteristics of a concrete mould (known as "shuttering") by the clerk of works:

> According to the Contract Quality Plan, queries raised by the RE or their staff should involve recording the problem, finding the answer, and filling out a 'works record', which would be sent to the site office, placed in the dayfile, and a copy sent on to the RE.
>
> Accordingly, the graduate engineer filled out a works record form with the problem request and sketched a diagram of the concrete shuttering and the setting it was placed in. He telephoned <someone> off-site, and discovered that the information he needed about using the shuttering was in the advertising/promotional leaflet sent out by the shuttering company, and was held on file in the team office.
>
> The information was lying on one of the foremen's desks, who had been looking through it with an eye to ordering more materials. The engineer read off the technical details from a table on the leaflet and added this information to the form.
>
> The engineer then posted the works record to the site office for inclusion into the dayfile for circulation. As a works record, no accompanying information was required because the form of the document meant that it would always be processed in the same way. Due to the slow speed of the internal postal service, the engineer later went back on site, located the clerk of works and reported his findings personally.

In this case, knowledge distribution occurred over the participants involved (graduate engineer, unknown telephone informer, foreman, clerk of works, and RE), and artefacts (the work record, dayfile, sketch, leaflet). This involved the use of different channels of communication (spoken, postal, and telephoned), each with different qualities for the transmission of the information. The ORGANISATIONAL structure (in the Contract Quality Plan) determined who had responsibility for various features of work. However, the work itself was performed through social and contextual mechanisms, with the ORGANISATIONAL structure functioning as an (incomplete) resource for the allocation of work, rather than an absolute rule set.

## A.5 Summary of Fieldwork

The design process was described as involving a cycle, incorporating data collection (an ongoing process), framing of the problem (through creating a set of specifications), solving the problem (in abstract terms), organising a means of activating the (abstract) solution, then implementing the design in a physical construction. Much of the work appeared to involve the setting of specifications and unearthing of constraints to discover the boundaries of the design space. The final phase of design appeared involved reporting on the outcome of the implementation (success or failure in matching the designed solution to the design problem, within the specifications and constraints), which was possible to utilise in the next cycle of design in the information gathering phase.

Work was distributed over the collaborating designers through a variety of means through which the task was decomposed. This involved the breakdown of the task into smaller and smaller sub-problems that could be resolved through simple design solutions, for example bracing beams with struts, to achieve an adequate load bearing strength. However, task decomposition necessitated bringing these component parts back together again in a coherent structure to meet the high level design specifications; for the example above, this might mean ensuring that these beams did not obstruct access to other areas of work.

The technical work performed by the engineering designers at both of the projects studied (see also Appendix B) involved similar patterns of activities. Both studies demonstrate how the physical environment and social organisation are major determinants of the actions performed in design. A central feature of design involved the use of artefacts of many kinds, in the use of drawings, but also other artefacts that represented non-spatial and more transitory forms of information.

The design artefacts were generated by re-representing information from the site, or from other artefacts themselves generated elsewhere in the design process. They included a number of different representational forms, including text and speech as well as diagrammatic and tabular forms.

Maintaining control over the processes of engineering design was an integral part of the engineering design process observed in the fieldwork. Control of the design artefacts was deemed to be of critical importance in this management of the design process. Only controlled representations were allowed an 'official' status in design work, although in practice the design workers predominantly used unregulated representations in the day to day operation of their work.

# Appendix B

# Field study 2 - Consulting Engineers

## B.1 Narrative

Walking through the entrance to the office I could feel a sense of tradition in the atmosphere. Glossy magazines and trade brochures were piled neatly on glass topped tables in the waiting room. There was an air of quiet competence in the air; the secretary took my details and handed me a security pass, then telephoned my contact. We arose in a silent lift to the fourth floor, and entered into an open plan office area. To my left were several large screened computers running CAD software, and all around, smartly dressed people worked quietly at their desks. Occasionally, they would walk over to other people's desks, smooth out large sheets of paper, and discuss these in hushed tones. A desk had been prepared for me - would I be requiring access to a computer?

The first day on the site was quite depressing - here I was to study communication, to see how engineers co-ordinated their activities in design, yet they barely appeared to speak to one another, and then only in hushed tones that did not invite further investigation. The next few days were more enlightening - I learned who was working on particular areas of various projects, and began to feel more a part of the process. I attended a number of meetings, both at the company offices and at the other ORGANISATIONS involved with the project, eventually becoming a fixture and having project related mail delivered to me alongside the rest of the design team. Nevertheless, the processes and procedures that the engineers used to perform work and to co-ordinate their planning activities were still largely concealed, and only by wading through a mass of project documentation was it possible to learn something of the nature of the work and its co-ordination; in a well co-ordinated activity, continuous communication and monitoring was not required. The design proceeded in a well practiced process operating within a socially and historically embedded fabric, and only when serious conflicts or disagreements arose did these procedures break down to reveal something of the complexity underlying the co-ordination of these activities.

## B.2 Field study of Consulting Engineers

The study was carried out the 'Building Engineering Group', or BEG (with around 50 employees) of a consulting engineering ORGANISATION (ACEO). At the time of the study, the BEG was particularly involved with a project to design a purpose built office block on top of an archaeological site in the City of London, to be called 'The Roman's House'[1]. A small unit within the group was involved in the design of the Roman's House, and this project was followed most closely, although other projects were also examined in less detail.

The BEG offices were located in London, a twenty minute journey by taxi away from the building site. The other project partners (architect, client, surveyor and contractor) were all co-located in an office block beside the site. At the time of the fieldwork, the foundations had been dug out, and the piling was being drilled into the ground to support the substructure.

The Roman's House project was a project involving a 'partnership' between several different commercial ORGANISATIONS, each of which took on a responsibility for aspects of the construction process, of which ACEO and BEG were a partner. The project involved the design and construction of a 10,000m$^2$ office block in central London; it was a 'Design and Build' project, contracted by a client, to a construction company. The BEG were contracted to the construction company (the contractors), and operated as the engineers to the project. The client was closely involved in the project and they were attempting to implement a close working partnership between the collaborating ORGANISATIONS involved with the project. However, this was at variance with the traditional mode of construction, based on contractual obligations to each other. Several other organisations were also involved in The Roman's House project, including the client, construction company, architect, electrical contractors, a piling company, quantity surveyors, City of London town planners, a consultant archaeologist, an archaeological authority and other minor stakeholder groups.

The work of the BEG was ongoing, having been initiated about a year before the fieldwork and expected to finish in another nine months following it. The early stage of transforming the architects drafts into engineering drawings for construction was nearing completion, and minor details for the 'fit-out' of the building, including building services and other non-structural features was beginning. These fit-out elements would have to be integrated with the form of the building to ensure its structural integrity and in facilitating ease of maintenance and comfort for its occupants.

[1] A pseudonym.

The task of the BEG at The Roman's House had been to transform the architects conceptual drawings into constructable forms that could withstand the stresses placed upon them by their environment and ensuring that the design conforms to the appropriate regulations and standards. This process was drawing to a close and the BEG engineers were winding this up, finishing off a few last designs and were concentrating on checking the designs submitted by the other contractors to see that they conformed to the original designs, existing standards and the relevant CDM legislation. The BEG's task therefore included the design of the mechanical, electrical and structural aspects of the building. This required close collaboration both within the organisation (within the teams and between teams) and with other organisations to fulfil this. Their goal was to specify the eventual form of the planned structure to an appropriate level of detail that would allow the construction company to erect the building.

### B.2.1 The engineering unit at ACEO

Two teams within the building engineering group were studied, the mechanical and electrical (M&E, with a fluctuating number of around four engineers), and structural engineering teams (numbering around seven engineers). Each team had a simple hierarchy, involving a team leader and more junior staff. The structures and activities of the two teams are described in more detail below:

#### The M&E team

Because of close contacts with the M&E team, this area was the area chosen for detailed analysis. The M&E team were expected to work closely with one another to produce designs that would allow the closely related mechanical and electrical equipment to operate to the appropriate standards and specifications set by the contract and legal health and safety legislation. The M&E team was made up of a senior BEG managerial engineer (overall responsibility, but little project involvement), a project manager (managing all aspects of BEG's involvement with The Roman's House), an M&E project leader (co-ordinating the M&E engineering work), and a graduate mechanical engineer. Halfway through the study these were joined by an electrical engineer. The team was supported by a computer aided drafting (CAD) team and a secretary.

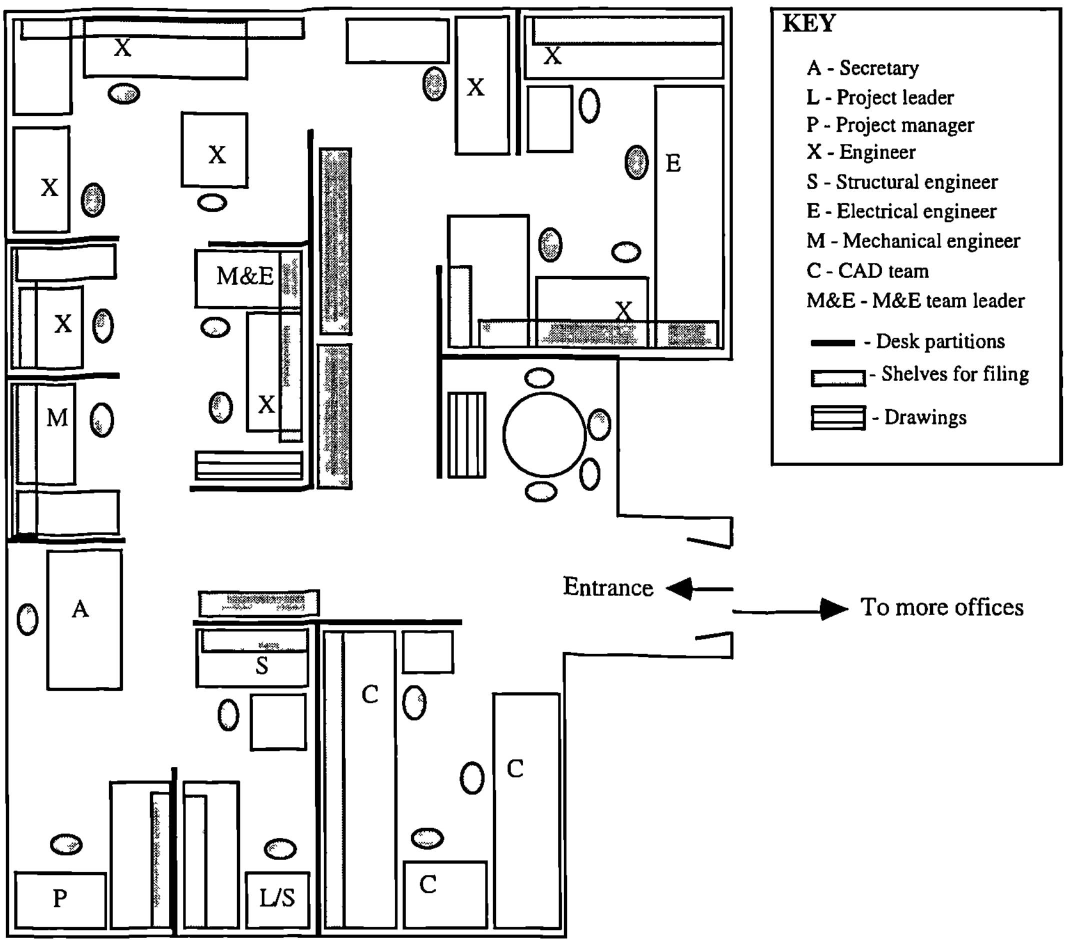
#### The structures team

The structures team did not compromise a central component of the study, but their interaction and partial co-location with the M&E team made their investigation both possible and important. The team members were distributed over three sites, only two being located in the BEG office in London, but including the structures team leader. The remit of the structures team was to produce designs that could withstand the loading placed upon the building frame whilst at the same time meeting architectural and other constraints, including those made by the M&E team.

**Integrating the teams**

The M&E team and the structures team worked closely together because features in the M&E and structural schemes had to co-exist in the completed building. This included co-ordination details, for example, so that voids, or empty channels, known as 'risers' to accommodate wiring and machinery, were placed in positions where they could be operated and maintained easily by service engineers. This involved extensive joint planning activities by the two teams. This collaboration was simplified by the teams being co-located in the same office area. The office layout was open-plan and it was possible to see, hear and easily speak to other people in the office. Team members could also draw on the experience of engineers working on other projects located in the same room. Their physical locations to one another are shown in fig. B.1.

fig. B.1. Layout of BEG office area.



### B.2.2 Organisation of resources in ACEO and BEG

ACEO is a large engineering ORGANISATION, based on a partnership, rather than public ownership lines. ACEO is described as being organised 'laterally rather than hierarchically' in structure, without long bureaucratic channels through which information and communications must pass. ACEO is made up of a number of building engineering groups and other engineering disciplines, and many of which are co-located in and around a central square. Some of the services that support the cohesiveness of the ORGANISATION are co-ordinated and run by central bodies throughout ACEO, such as 'ACEO Computing Services'.

The engineering teams have a number of resources available to them. One of the main features of design is the CAD system; this enables the engineers to input their designs into a central design model and print this out as a 'drawing'. Engineers do not operate the CAD system themselves, usually marking up drawings and asking the CAD team to create or modify the designs. However, ACEO envisage CAD to be more than simply a means of creating drawings:

> *"An aspect of CAD is that it can assist the process of design by allowing us to co-ordinate information between different members of the design team and, along the way, to produce a more consistent and useful description of the entire project"*

(ACEO internal document - 'CAD Good Practice Guide').

The models in the CAD systems are seen as 'shared data'; tentative data is kept in the form of a drawing, to demonstrate that it is not yet reliable enough to direct design from. One of the more important forms of drawing that is intended to be used within ACEO is the 'co-ordination issue': these are only issued internally and are used to aid the co-ordination activities between the different engineering disciplines. Once marked up, these are incorporated into the final set of drawings.

Computers were rarely used by the engineers; most of the machines (other than for CAD) were used in word processing, for faxes, presentations and basic calculations. All of the engineers had access to a machine, although they did not have one each.

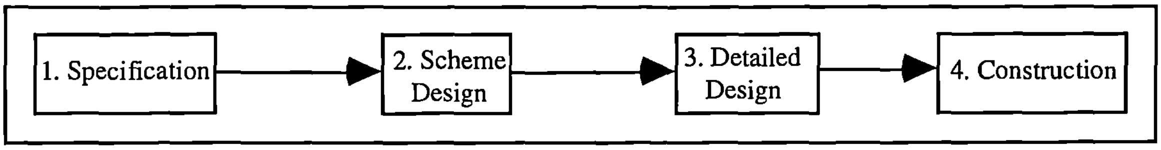
### B.2.3 Quality assurance at ACEO: rationale, process and practice

During design, many documents pass from the designers to architects, clients, contractors or other stakeholders to the process; in return, there is a mass of incoming data which must be channelled to the appropriate people. Each person has their own responsibilities for particular parts of the project and should know of the lines of reporting and responsibility for this. All of this must be controlled in the organisation of the project (performed through the organisation of BEG itself). To enable this to be done unambiguously to avoid contradiction, the BEG has opted to set this out in a document, forming a quality assurance (QA) for their 'product'. This was awarded certification by an external body; one of the benefits of such certification is that it lends the ORGANISATION commercial credibility, even though it must maintain the QA system even where it is over-cumbersome.

Quality assurance forms a major part of the engineering system in BEG. Document control is an important factor in the QA process, to ensure that duplication of effort does not occur, that only current documents and drawings are in circulation and that the dayfile is archived appropriately. The document control process is managed by the mail office for the whole of BEG, and for The Roman's House project by the office secretary.

### B.2.4 Design work at ACEO

In general, there are a number of discrete stages that design was said to go through as it progressed to completion:




1 - Initial specification - derives from client specification, with involvement from the architect.

2 - Scheme design - created through collaboration, largely between the architect and the consulting engineer to produce a workable model for construction.

3 - Detailed design - where the details of the scheme design are fleshed out so that the building meets safety regulations, design specifications and other constraints. The Roman's House was at this stage during the period of study.

4 - Construction - the contractor works to the 'for construction' drawings to build the design.

Stages 3 and 4 are those where ACEO are most involved as consulting engineers. It is at these stages that their skills in engineering are used in transforming the architect's aesthetic design into a structurally sound, habitable and constructable building design.

### B.2.5 Organisation of resources

**Design work on the project**

At the time that the field work was undertaken, the engineers had completed much of the work of transforming the architects drawings into structures, and were engaged in developing the interior of the building, prior to 'fitting out' the structure with internal equipment, such as toilet facilities, lighting, fire management, temperature control and lift machinery. Whilst the fitting out process involved the design of features internal to the building, these had to be integrated with the building structure. Occasionally, conflicts between the structural design and the fittings would have to involve alterations to the structure (minor, in all of the cases observed), to accommodate these changes.

The engineers in the BEG involved in the design process variously described design work, as 'producing an integrated solution to achieve a goal', 'a compromise between form and function', 'an ongoing process throughout the life cycle of the project', moving from concept to detail, and as having two versions - a published and an unpublished form. The 'published' form was that designers 'work with the architect to develop solutions to problems'; the 'unpublished' one, 'to just make sure you meet the constraints'. Problem solving was also described as 'adding value, but not cost...and taking a set of criteria and developing an *appropriate* solution'. Dialogue was seen as important by most informants, indeed a central component, and collaboration and communication was said to be crucial to this process.

The design activities observed in the fieldwork generally involved minor design components had to be incorporated into the larger design scheme. This involved integrating the fit out materials, such as the lighting control systems, with the structural design, and taking into account the physical limitations and spatial requirements of the materials. In some cases, as price reductions or reliability considerations on materials were involved, the choice of materials used had to be changed at the last minute. The design engineers therefore had to allow for these variations and be prepared to modify their designs at a late stage in the process.

In comparison to the study of the civil engineers (Appendix A), the BEG's engineering designers were only involved in a single phase of the design cycle, taking the previously collated information as an input and outputting their proposals for structures to the construction company for use in the construction.

**Division of work**

The task of the BEG was to develop the architectural building design into a constructable and habitable office block. Due to the enormity of the problem, the design work performed by the BEG was broken down into smaller design problems. The huge size and complexity of the task, and the stage that the project was at, meant that these sub-problems ranged from providing solutions to minor queries, such as where to situate electrical sockets, to more substantial decisions about the location of load bearing walls and the integration of computer operated building control systems. Division of labour on the project was therefore problem based, involving groups of designers who dispersed once the design problem had been resolved to an acceptable degree. In many cases, designers were involved in multiple sub-groupings (possibly drawn from several ORGANISATIONS) which existed for only a few days or weeks, until the problem had been resolved, and these groups shrunk or grew according to requirements.

Within the BEG, design tasks were allocated by the structural and M&E team leaders, who allowed a high degree of autonomy once the initial work had been assigned. Team leaders managed their workers loosely (depending on the experience of their subordinates), and often only checked the eventual design of the delegated sub-component, rather than monitoring the progress of individuals. This was partly because of their own design activities and heavy meeting schedules; team leaders were also often involved in multiple activities across a number of projects, and had little time for management activities.

The design problems were largely identified from the architectural drawings. The generation of engineering designs was accomplished by taking the architect's designs and incrementally substituting structures that could physically support the proposed forms. This formed the structural engineering component of the design work. Components also had to be designed that could fulfil the mechanical and electrical demands of the proposed machinery and electrical fittings, which formed the M&E engineering design component. Occasionally, the architectural designs would have to be modified to fulfil these specifications, although these had to be negotiated with the architect. As the designs were developed, conflicts could occur with other areas of the design; to ensure that these conflicts were resolved, the engineers had to be aware of the work of the other designers, adapting their own designs to achieve a global solution, integrating *all* parts of the building design.

## B.3 Design activity in building engineering

The inputs to the structural design phase included the outputs of the information collation phase conducted by the other ORGANISATIONS involved with the Roman's House, including inputs from the architect, client, construction company, suppliers, quantity surveyors, the City of London Town Planing Authority, archaeological museum, and the consultant archaeologist. The BEG had to operate upon this set of inputs to produce designs that would meet all of the specifications determined by these stakeholders (although many of these specifications were subject to negotiation and compromise). In addition, several other inputs had to also be considered, including generic prior knowledge by the BEG engineers about building design. The BEG's engineers also had access to previously created designs which could be re-used with little additional work, excepting their being checked to see if they met the constraints imposed by the local requirements of the stakeholders, safety regulations and other standards.

Building design involved engineers taking the specifications from architectural drawings, supplementing this with information arising from communications with the architect where the drawings proved inadequate, and generating a solution that fulfilled the requirements set. Designs also had to incorporate the demands of the other stakeholders. The design process therefore required determining the structure of the architects vision from the architectural drawings and other means of communication, producing draft copies of proposed designs, checking that the requirements of the various parties involved were met, and negotiating with these parties if conflicts arose between them. The final output of the BEG involved passing the final design representation (a drawing) to the construction company for use in generating their work schedule and in construction of the building.

Collaboration between the engineers in the BEG was simplified by co-location of the two teams in an open plan office, allowing the engineers to see, hear and speak to the other designers on the project. This was true for all of the M&E team who were situated within several metres of one another, separated only by low partitions (1.25m high). The structural engineers were distributed over several sites, but three of their members (including the senior engineer) were in the same office, grouped together, although several metres away from the M&E team and separated by several partitions. This co-location also allowed team members to draw on the experience of engineers working on other projects but within the same room. Regular informal meetings and communication took place within and between the two groups as they went about their design activities, often bound up in the social atmosphere of the office. A meetings table was located centrally in the office space, which allowed the whole room to overhear discussions, keeping those present in the room abreast of developments and allowing them to join the meeting, or shout across the room to add to the discussion.

Two main forms of communication were observed, one brief and the other involving longer, more involved discussions. Brief communications typically involved queries, where a person needed an answer to a direct problem that they understood, but did not know the answer to (i.e. a well-structured problem). These communications involved engagements that might last as little as a few seconds, they usually took place at a desk or in a corridor, could involve any of the people in the design process; they had a high degree of closure, and were frequent. The longer design based communications that took place typically involved the solution of a less well understood problem (ill-structured problems, Simon, 1973). In these wide ranging discussions, the engineers would discuss what they knew about the problem, ways that they might solve it, and how changes might affect the rest of the design. Often, these discussions would conclude without generating a solution, to be followed up with further discussions, or a document. These engagements were characterised by extended meetings (around twenty minutes or more), often with more than two people, and generally involved senior, rather than junior, engineers. They often took place away from the engineers' desks and involved the use of artefacts, such as drawings or sketches.

Communication between the two groups were generally of longer duration than within a group, and involved several participants. These communicative events almost always involved the leaders of the M&E and structures teams. Much of the communication between the M&E team and the structures team was formalised, generally involving extended discussions. They often involved more than two people and took place around the meetings table, resulting in a drawing, document or memo that would be circulated to the two teams.

One of the most common means of providing co-ordination between designers working on different aspects of a design at the BEG was through the creation of 'co-ordination drawings', where the two or more models of design, held in a variety of formats (mentally, on sketches, on various formats of drawing, or on CAD models), could be brought together on a single representation - a drawing - to examine where conflicts might arise. A combined representation, agreed upon by the disciplines involved (in the fieldwork, structural and M&E), could then be generated with less room for ambiguity or future misunderstanding. The informants found this to be the best means of co-ordinating their different sub-tasks to generate an integrated design solution.

Communication about the design also involved engaging with stakeholder groups external to the BEG. The location of the other groups, half an hour away by taxi, across central London, was a major determinant of the form and frequency of the communication that took place between the ORGANISATIONS[2]. Each ORGANISATION was responsible for particular aspects of its design and construction. Within the phases of the design (described in section 4.5.3), most communication between the partnership groups was handled through meetings; dates for work completion were set in the IRS (information request schedule), and attached to the meeting minutes - for the BEG this would involve generating a drawing for comment or construction. In between the meetings, a flow of telephone calls, faxes, posted drawings and letters

[2] Informants noted that when multiple organisations were co-located (as in a previous project), these patterns of communication differed substantially.

provided a medium for co-ordinating minor procedural details between the ORGANISATIONS.

Members of the different ORGANISATIONS would meet at these regular and pre-designated times to discuss the state of the building and problems encountered in the design process. These meetings often lasted several hours and were used to reach agreements on undecided details of the design and to partition responsibilities for particular parts of the project between the ORGANISATIONS. An agenda would be posted to the participants before the meeting, and minutes circulated afterwards. These documents set the underlying structure to the solution of the design problems: queries would be noted, transformed into actions and assigned as responsibilities for particular people or ORGANISATIONS. At subsequent meetings, these items would be checked to see if they had been completed.

Through discussions with the other project stakeholders, ideas were clarified about how to generate a design, drawing information from the client and architect about their expectations, and relating these to the site conditions, materials and other resources available. These meetings were generally scheduled (up to a year in advance) on a weekly or bi-monthly basis, with exceptional problems requiring meetings to be arranged when necessary (an unusual phenomenon, and not observed in fieldwork). Many such meetings were observed, each relating to different aspects of the project, known as 'Project Team Meetings', 'Site Progress Meetings', 'Design Progress Meetings', 'Design Meetings', 'Mechanical and Electrical Meetings' and 'Lighting Control Meetings'.

Informal communications, other than the formal meetings between the stakeholder ORGANISATIONS, almost universally involved telephone conversations; these might be combined with a fax, to transmit spatial information, which could then be discussed verbally. Faxes were mainly used to transmit spatial information, or tables of written information too complex to be read out aloud. Telephone communications were almost always brief, except on occasions when the participants were unable to meet face to face. The purpose of the calls was usually to discover information, or to update people on minor changes. Telephone calls were also used to arrange meetings to discuss complex problems, to allow other people to enter the dialogue, and so that the participants could 'communicate more naturally' (informant's words).

A third form of communication between the ORGANISATIONS involved the transfer of design representations, in the form of artefacts. These generally involved paper documents (text or drawings), but in some cases (between the architect and BEG) as computer models on floppy disk. These formed an important, but separate and more formally managed, component to the communications documented above. These documents took several forms, indicating the status of the representation (for comment or finalised), and which could be critically examined to see how it matched the expectations of the different groups.

Where the design stepped through the various stages from specification towards a final solution, there was a formal, explicit transition, marked by the completion of finalised drawings and other documents; these included the architectural drawings, co-ordination issues, drawings for comment and drawings for construction. Once each stage had been completed, new developments could be built on the back of these prior decisions taken. However, whilst these stages appeared to be discrete units in the design process, they occasionally had to be modified in the light of changes to these completed stages. In addition, some errors, omissions and ambiguities meant that what appeared to be firmly specified was discovered at a later date not to be. Changes also occasionally had to be made as legislation, financial or physical constraints became clear. It was at these transitional stages that informants noted that particular care had to be taken so that minor changes would not cause drastic knock-on effects throughout the rest of the design. The formal documentation was therefore a means of drawing a line under work that had been completed, and returning to change these stages was only permissible if major problems occurred in the design. Change to the completed design after one of these transitions could result in a financial penalty for the ORGANISATION that requested such a modification.

The end result of the meeting or meetings between the BEG engineers and other stakeholders would result in the creation of a 'drawing for comment' by the BEG. The 'drawing for comment' would be the first externally available (outside the BEG) unified representation of the proposed design. If no comments were made about it, the drawing was 'passed' by all of the stakeholders. In any other eventuality, the design would go through another cycle (or more), as it was modified to incorporate the comments made by the stakeholders, before being resubmitted.

The final outputs of the structural design phase for the Roman's House were the finished drawings, agreed upon by all of the parties involved, and stamped 'for construction'. These were sent by the structural or M&E team leaders to the construction company to use in the next phase of the design cycle. This ended the BEG's responsibility for that design problem. However, as the BEG was involved in many such design problems in the project, the designs created could have repercussions upon other design problems in the construction project that they would have to resolve.

## B.4 Features of design in building engineering

### B.4.1 Inter-organisational activity

During the process of design, many documents passed between the engineering designers, and then out to the architects, clients, contractors and other stakeholders; in return, there was a mass of incoming communication which had to be channelled to the appropriate people. Each individual had their own responsibilities for particular components of the project and (should) know of the lines of reporting and responsibility for this. To enable this to be done unambiguously and to avoid contradiction, the BEG had set this out formally in a quality assurance system (QA). Document control was an important factor in the QA process to ensure that duplication did not occur, and that only current documents and designs were in circulation. The QA system specified the forms of artefacts to be used within the BEG and these were rigidly adhered to. However, there was less control of the use of artefacts between ORGANISATIONS, leaving more scope for misunderstanding and confusion. This was a problem for the project, as out of date drawings were said to be occasionally used in error.

The informants noted that one of the reasons that so many lengthy formal meetings were required between the BEG and the other ORGANISATIONS on the Roman's House project was that the site was distant from the offices of the BEG. The telephone was too unnatural and clumsy (informant's description) a method for communication and the site took a long time to visit (half an hour). Due to this distance, engineers tended to try to do as much as possible without having to ask minor questions, something that was not conducive to a smoothly integrated design process. Projects where all of the stakeholders were co-located were seen as the best way of improving the design in a project. Unfortunately, this was unfeasible in relatively small projects for BEG, such as The Roman's House, where the same engineers were working on a number of different design projects.

### B.4.2 Patterns of communication

Formal engineering design processes were defined in the quality assurance system, which specified how the engineering designers were to operate. However, the QA system was not applicable to all situations, and only proscribed methods to be used in the transitions of documentation relating to the design process. Whilst the project related documentation formed a major component of communicative activity and as a mechanism for co-ordinating the design activities, the documentation did not comprise all of these activities. The QA system was therefore not used in the management of moment by moment, ad hoc interactions, either between the engineers within the BEG, or between the BEG and other stakeholder groups.

Paperwork for the project was maintained in the dayfile. All letters and other information relating to the project sent to or from the BEG were entered into the Roman's House project dayfile, maintained by the mailroom and locally, by the secretary. All incoming correspondence (generally letters and faxes) was entered into the dayfile and a copy sent to the recipient. The team participating in the project had to sign the dayfile on a daily basis and initial the documents directly relating to themselves to demonstrate that the material had been read and understood. This was intended to increase information related project awareness, although in reality, it created a new problem by making too much information available for the engineers, resulting in information overloading. Comments were also occasionally written onto documents in the dayfile, such as 'problem resolved', followed by a date, or possibly referring the reader to a subsequent document or drawing.

Informal, socially mediated mechanisms of co-ordination were managed on an ad hoc basis, in the naturally arising interactions of the collaborating engineering designers. These included the passing of sketches and memo's between themselves to compare their conceptions of the developing design. In addition, perceptual monitoring was used (particularly within the designers at the BEG), as people's physical actions could be observed and the artefacts of work (such as 'desk litter') were visible, making the other co-located designers aware of the activities being performed and the decisions being made.

### B.4.3 Artefacts in the design process

A wide range of design artefacts were used in the building engineering design process, many of which appear to be universal across various engineering disciplines. The artefacts described below were used extensively, both within and between the teams in the BEG, and between the stakeholder ORGANISATIONS.

The most obvious part of the design process was the construction and use of drawings. Several hundred drawings for the project existed, often in multiple copies, and these would be frequently updated. These drawings littered the workplace, often several layers deep on desks; in conversation, the words 'design' and 'drawing' were often used interchangeably, denoting the importance of the drawing to the design activity. However, the physical nature of the drawing was observed to fulfil a number of functions. Whilst the drawing encapsulated many of the features of the design, the representational form of the drawing on paper also allowed it to be manipulated and communicated in a way that an abstract representation of the 'design' could not.

Throughout the BEG and other ORGANISATIONS, various forms of drawings existed, representing the design at particular stages. These drawings symbolised several different meanings, and changes to the form of the drawing often denoted a transitional change in the state of design process. Particular forms of drawing denoted problem ownership, or a change in the status of the design process. For example, the architectural drawings were the property of the architect and were used to communicate the final architectural design to the other stakeholders; signatures and stamps on the drawings also denoted who had assumed ownership of the design and who to query if problems had arisen.

The drawings could also be marked and annotated; indeed the drawings on the engineers desks were usually covered in various colours of highlighter pen, identifying the changes that had to be made to them. They were also sketched and written onto, both for personal benefit and to pass on to others. When talking to the other designers, these drawings would be opened up and gesticulated at; comments made in the meetings were occasionally written directly onto the drawings. When it was not possible to have face to face meetings, the drawings could be faxed (after being photocopied and 'shrunk') to the recipients. These drawings would occasionally be annotated and faxed back (with a resultant loss of quality). Drawings were however, too slow to produce in meetings: as a consequence, they had to be prepared in advance of the meeting and changes distributed after it. On one occasion in a meeting, a drawing was forgotten: the meeting was postponed until it was fetched several hours later. Perhaps surprisingly, sketches were infrequently made, possibly because they were unofficial and did not form a part of the systematic, quality assured, design process. This may account for why that they were rarely used as an enduring artefact in design.

The drawings also embodied the mathematical calculations ensuring that interactions of the component parts had been checked: this would be evident on the status of the drawing, denoted by the stamps on it (e.g. 'for comment', 'for construction') and the initials of the senior engineer who had checked it. The drawings were also occasionally annotated with a comment about the calculations, or with a file reference where they might be found. An 'eyeball check', or comparison of the drawing (mapping onto two dimensional reality) to the engineer's prior experience of such a form to see the plausibility of its structure, was also described as a frequently used check on a drawings validity.

The design of the building within the BEG lay in the CAD (computer aided drafting) system. This CAD model formed an internal computer representation of the developing design. The model could be viewed on screen, or printed out as a drawing (the only form of output used by the engineers). The models were maintained and created by the CAD operators under instructions from the engineers. Interestingly, the engineers rarely used computers; it was not that they could not, but because they did not need to, this being performed by the operators.

The walls of the BEG and the other stakeholder offices visited were covered in pinned up drawings and other printouts or computer generated images of the design. In meetings, these would be constantly referred to, pointed at and compared to other artefacts. They appeared to provide a common, visualisable object to which people involved in the design, but with different skills and perspectives, might gain a common understanding of the problems being discussed. In the office of the client, a two metre high model of the completed building had been created, and in meetings, speakers would occasionally get up and point to the locations that they were talking about, moving their hands as if they were twisting parts of the structure to a different angle or 'dragging' a part of the structure to another location on the model.

Email was used extensively within the BEG: it was considered to be a useful mechanism for communication because it was easy to generate information for sharing, by allowing information to be forwarded electronically to other relevant parties, rather than circulated as paper copies. It also acted as a 'personal bulletin board' to remind the other engineers about meetings, events and other activities. However, this did intrude into the domain of QA, and because these electronic documents were not (QA) controlled and had no legal basis, email did not have the same significance as the drawings or paper documentation in the dayfile, and was not subsequently used to discuss design related details, only to the *processes* of design, such as proposing dates for meetings and to say when they were going to be away from the office, to which the same ORGANISATIONAL significance was not attached.

Many forms of artefacts were used in the design process, as aids to the individual, as devices for communication and as a means of organising the developing design representations. These artefacts included the drawings (of various kinds), the CAD system, a scale model, the dayfile, a mailing system, a range of annotation and marking tools, desks and walls to pin design representations onto, paper duplication and shrinking technology (photocopier), communication technologies (telephone, fax and email), and calculation tools. Maintaining control of these artefacts was critical in ensuring that only the appropriate documentation and design artefacts were in current circulation. This was a major problem with the project because the engineers became buried under the bureaucratic residue of the communication and artefact control systems, and the work activity became as much one of system maintenance as of design itself.