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:

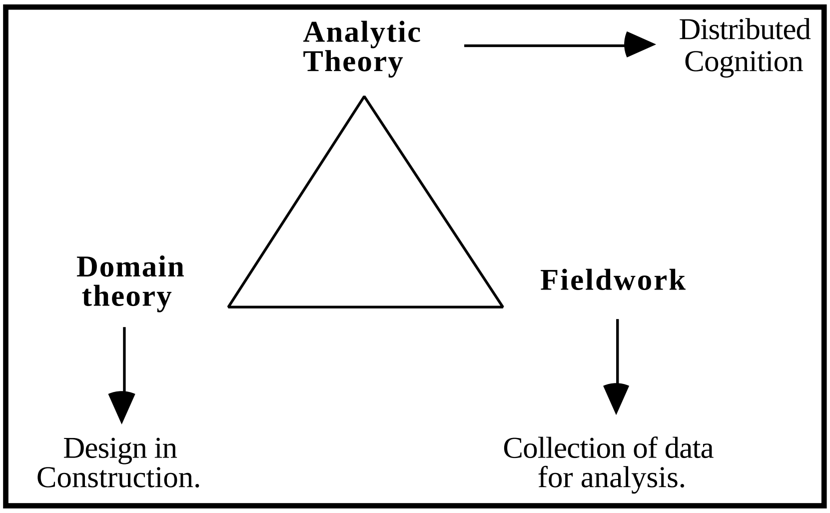
Analytic theory - this is the role of distributed cognition. Distributed cognition forms the theoretical basis framing the analysis. It provides a framework that structures the fieldwork into a form that can be used to describe the salient features about the co-ordination and performance of work.

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

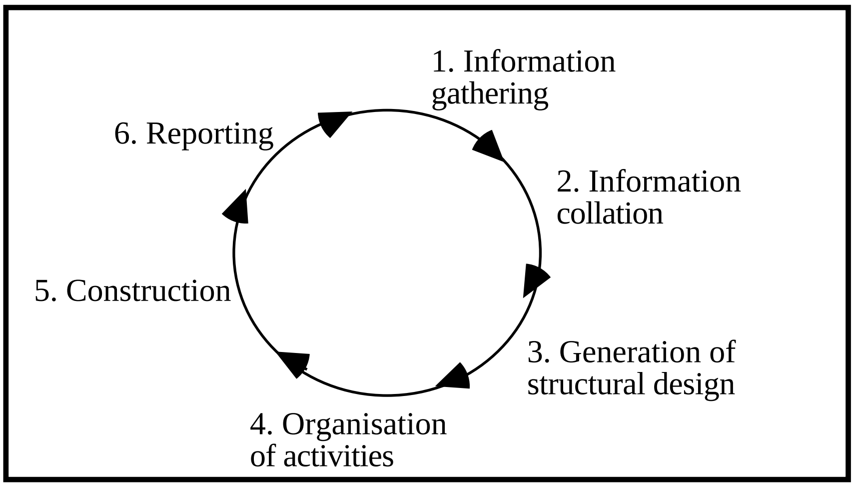
To investigate the collaborative performance of design within the construction industry, the three areas that make up the thesis, in data collection, analysis and their use in systems design need to be made explicit. Each of these is considered in turn below, and are used to guide the research in the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