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,

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

or previously negotiated division of labour, the interactants do the work that they are able to (or willing to do), 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-

[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).

national ventures are planned - another apparent industry trend, itself made possible 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.