Chapter 7

Conclusions and Issues for Further Research

7.1 Summary of the Research

7.1.1 Contribution to knowledge

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

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

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

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

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

7.1.2 Domain sensitive research findings

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

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

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

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

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

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

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

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

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

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

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

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

Technology can be used to support this by providing explicit feedback on the progress of implementation into the structural design phase.

7.1.3 An evaluation of the study

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

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

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

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

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

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

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

7.2 Issues in collaborative design

7.2.1 Expanding classical conceptions of design

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

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

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

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

7.2.2 The media of design: representations and artefacts

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

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

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

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

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

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

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

7.3 Issues arising from the research

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

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

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

7.4 Conclusions drawn from the research

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

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

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

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

7.5 Future directions for research

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

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

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

A further research question would be to examine the impact of the technologies developed from the studies, in their adoption and use in practice, and how this would change the distributed cognitive processes of the functional system. This is currently

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

being undertaken by the author as a part of the CICC project, and a preliminary study is underway. Further research would help support the findings of the thesis, although the development and implementation of these technologies in the workplace is limited because these technologies are still undergoing technical development and implementation.

7.6 Endnote

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

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