Chapter 5

Data Collection - Collaboration in Construction

5.1 Overview

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

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

5.2 Studying the co-ordination of design work

5.2.1 Background to the field studies

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

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

5.2.2 Data collection

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

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

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

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

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

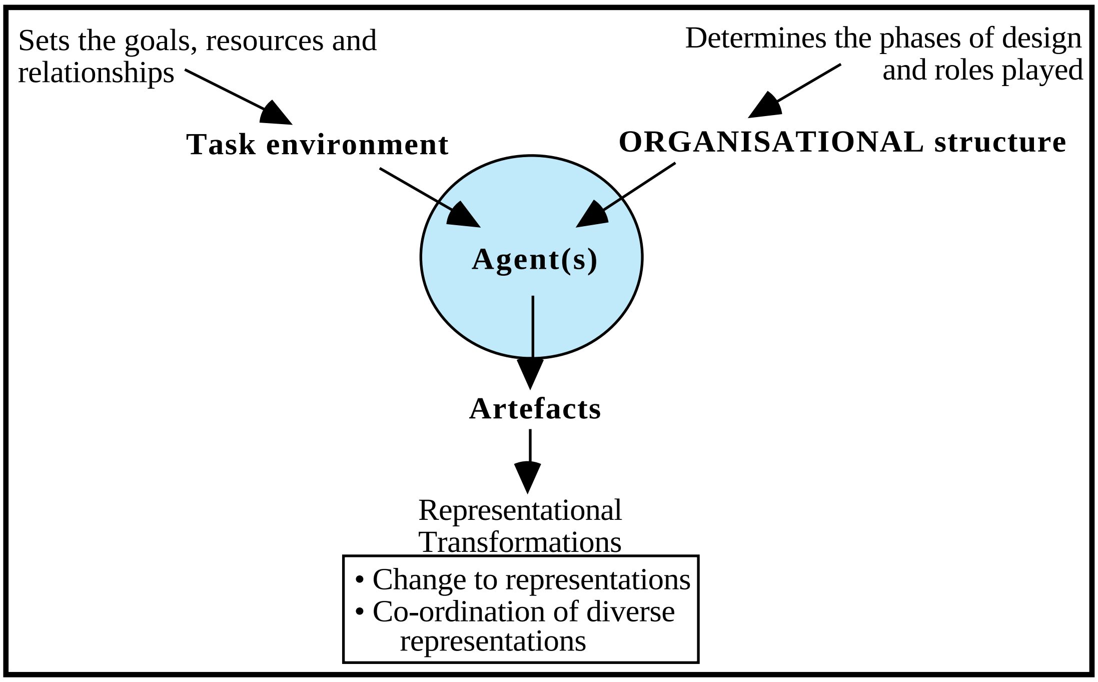
3. *Transformational work* - The inputs and outputs to the functional system and the transformations on the representations in information processing.

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

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

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

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



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

5.3 The task - construction work

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

5.3.1 Goals

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

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

5.3.2 Resources

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

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

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

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

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

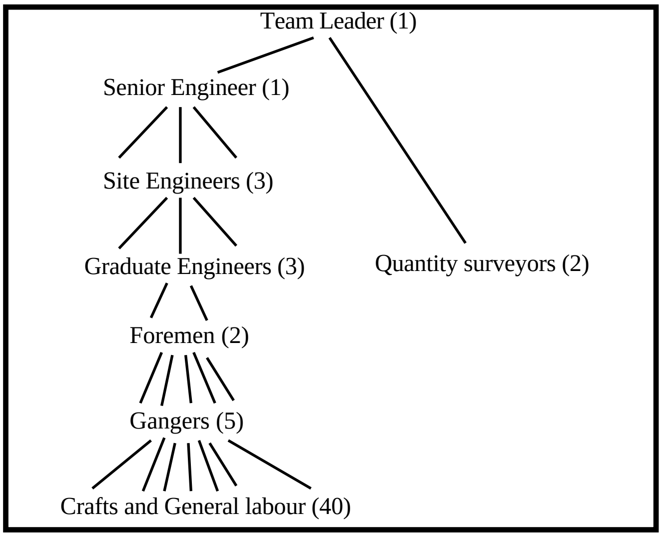
5.3.3 Relationships

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

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

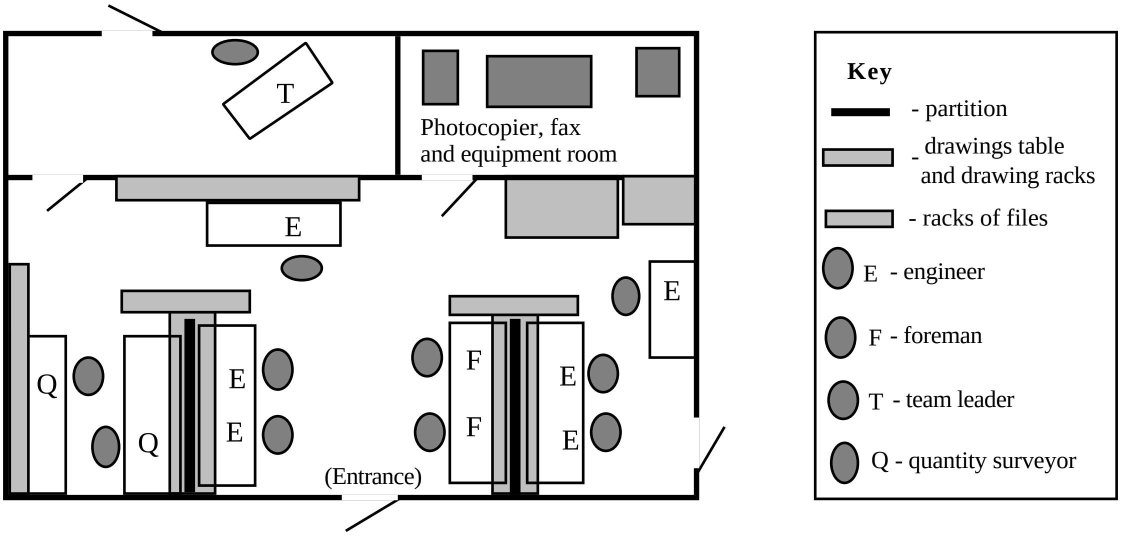
The ORGANISATIONAL relationships between the construction team members was organised in a hierarchy, which included a team leader, seven engineers (one senior, three site, and three graduate engineers), two foremen (senior work supervisors), five gangers (junior supervisors), the craftsmen and general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

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



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

fig. 5.3. Layout of construction team office



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

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

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

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

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

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

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

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

5.4 Organisational structures

5.4.1 Phases of design

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

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

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

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

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

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

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

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

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

5.4.2 Roles and responsibilities

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

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

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

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

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

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

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

5.5 Transformational work in design

5.5.1 Inputs, outputs and transformational activity

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

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

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

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

5.5.2 Computation and re-representation

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

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

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

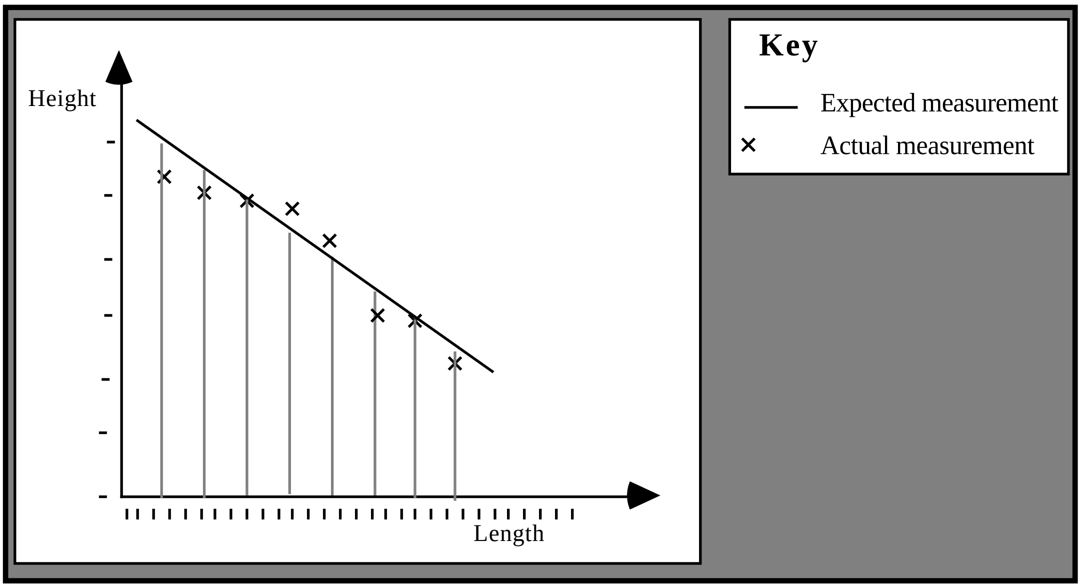
These are discussed below.

Change to media

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

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

fig. 5.4. Sketch of road gradient.



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

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

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

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

Modification of media

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

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

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

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

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

Bringing representations into co-ordination

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

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

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

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

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

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

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

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

5.5.3 Bi-directional movement of representations

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

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

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

5.6 Collaborative work in design

5.6.1 Communication and co-ordination

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

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

Put fig. 5.5. here

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

5.6.2 Context and planning

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

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

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

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

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

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

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

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

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

5.6.3 The allocation of tasks

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

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

According to the Contract Quality Plan, queries raised by the RE or their staff should involve recording the problem, finding the answer, and filling out a 'works record', which would be sent to the site office, placed in the dayfile, and a copy sent on to the RE.

Accordingly, the graduate engineer filled out a works record form with the problem request and sketched a diagram of the concrete shuttering and the setting it was placed in. He telephoned <someone> off-site, and discovered that the information he needed about using the shuttering was in an advertising/promotional leaflet sent out by the shuttering company, and was held on file in the team office.

The information was lying on one of the foremen's desks, who had been looking through it with an eye to ordering more materials. The engineer read off the technical details from a table on the leaflet and added this information to the form.

The engineer then posted the works record to the site office for inclusion into the dayfile for circulation. As a works record, no accompanying information was required because the form of the document meant that it would always be processed in the same way. Due to the slow speed of the internal postal service, the engineer later went back on site, located the clerk of works and reported his findings personally.

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

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

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

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

Senior engineer: ‘Yes’.

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

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

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

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

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

5.7 Summary

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

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

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

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

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

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