# Appendix B

# Field study 2 - Consulting Engineers

## B.1 Narrative

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

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

## B.2 Field study of Consulting Engineers

The study was carried out the 'Building Engineering Group', or BEG (with around 50 employees) of a consulting engineering ORGANISATION (ACEO). At the time of the study, the BEG was particularly involved with a project to design a purpose built office block on top of an archaeological site in the City of London, to be called 'The Roman's House'[217]. A small unit within the group was involved in the design of the Roman's House, and this project was followed most closely, although other projects were also examined in less detail.

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

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

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

[217] A pseudonym.

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

### B.2.1 The engineering unit at ACEO

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

#### The M&E team

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

#### The structures team

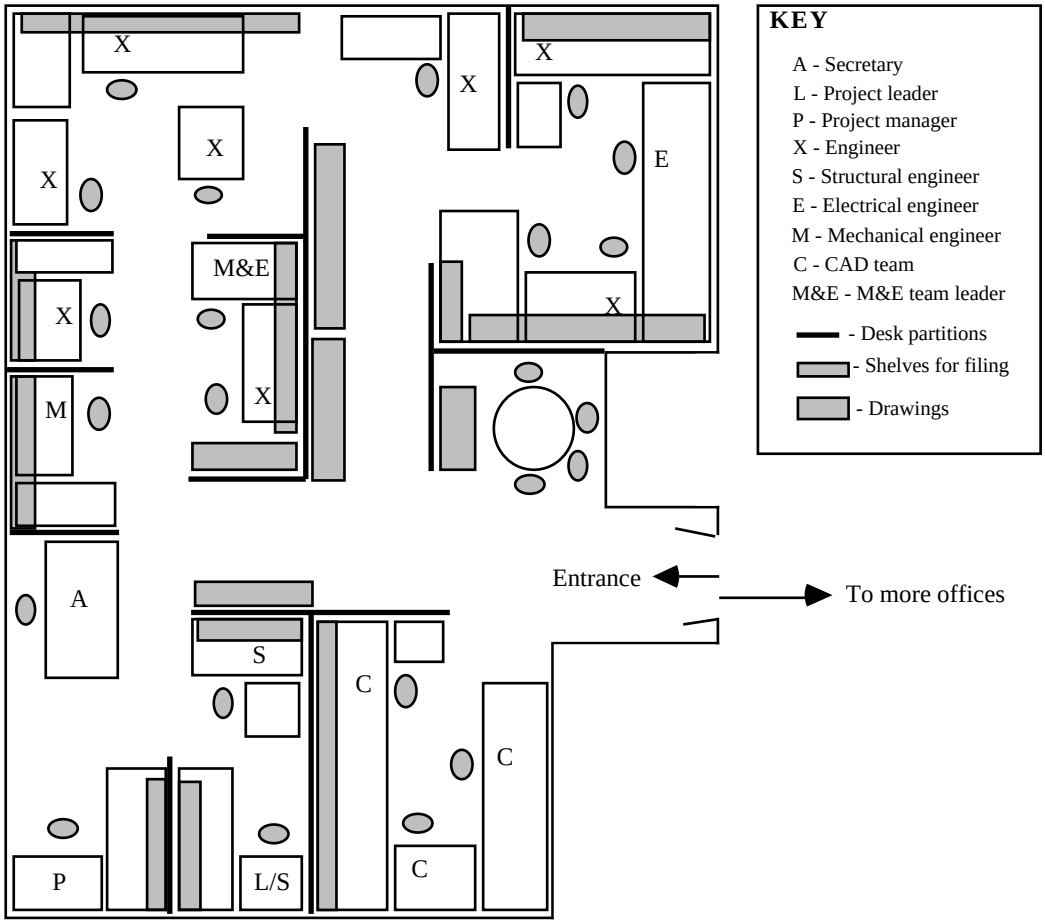
The structures team did not compromise a central component of the study, but their interaction and partial co-location with the M&E team made their investigation both possible and important. The team members were distributed over three sites, only two being located in the BEG office in London, but including the structures team leader. The remit of the structures team was to produce designs that could withstand the

loading placed upon the building frame whilst at the same time meeting architectural and other constraints, including those made by the M&E team.

### Integrating the teams

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

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



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

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

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

> *"An aspect of CAD is that it can assist the process of design by allowing us to co-ordinate information between different members of the design team and, along the way, to produce a more consistent and useful description of the entire project"*
>
> (ACEO internal document - 'CAD Good Practice Guide').

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

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

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

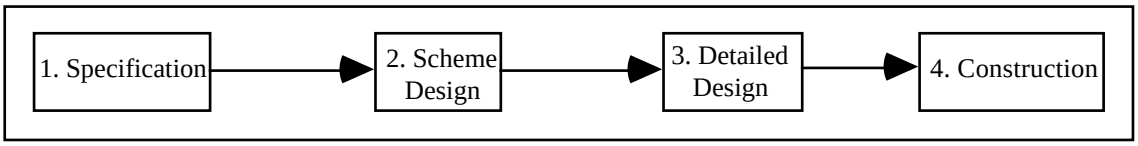
During design, many documents pass from the designers to architects, clients, contractors or other stakeholders to the process; in return, there is a mass of incoming data which must be channelled to the appropriate people. Each person has their own responsibilities for particular parts of the project and should know of the lines of reporting and responsibility for this. All of this must be controlled in the organisation of the project (performed through the organisation of BEG itself). To enable this to be done unambiguously to avoid contradiction, the BEG has opted to set this out in a

document, forming a quality assurance (QA) for their 'product'. This was awarded certification by an external body; one of the benefits of such certification is that it lends the ORGANISATION commercial credibility, even though it must maintain the QA system even where it is over-cumbersome.

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

### B.2.4 Design work at ACEO

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




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

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

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

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

Stages 3 and 4 are those where ACEO are most involved as consulting engineers. It is at these stages that their skills in engineering are used in transforming the architect's aestheti

t the fitting out process
involved the design of features internal to the building, these had to be integrated with the building structure. Occasionally, conflicts between the structural design and the

fittings would have to involve alterations to the structure (minor, in all of the cases observed), to accommodate these changes.

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

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

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

### Division of work

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

until the problem had been resolved, and these groups shrunk or grew according to requirements.

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

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

## B.3 Design activity in building engineering

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

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

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

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

a document. These engagements were characterised by extended meetings (around twenty minutes or more), often with more than two people, and generally involved senior, rather than junior, engineers. They often took place away from the engineers' desks and involved the use of artefacts, such as drawings or sketches.

Communication between the two groups were generally of longer duration than within a group, and involved several participants. These communicative events almost always involved the leaders of the M&E and structures teams. Much of the communication between the M&E team and the structures team was formalised, generally involving extended discussions. They often involved more than two people and took place around the meetings table, resulting in a drawing, document or memo that would be circulated to the two teams.

One of the most common means of providing co-ordination between designers working on different aspects of a design at the BEG was through the creation of 'co-ordination drawings', where the two or more models of design, held in a variety of formats (mentally, on sketches, on various formats of drawing, or on CAD models), could be brought together on a single representation - a drawing - to examine where conflicts might arise. A combined representation, agreed upon by the disciplines involved (in the fieldwork, structural and M&E), could then be generated with less room for ambiguity or future misunderstanding. The informants found this to be the best means of co-ordinating their different sub-tasks to generate an integrated design solution.

Communication about the design also involved engaging with stakeholder groups external to the BEG. The location of the other groups, half an hour away by taxi, across central London, was a major determinant of the form and frequency of the communication that took place between the ORGANISATIONS[218]. Each ORGANISATION was responsible for particular aspects of its design and construction. Within the phases of the design (described in section 4.5.3), most communication between the partnership groups was handled through meetings; dates for work completion were set in the IRS (information request schedule), and attached to the meeting minutes - for the BEG this would involve generating a drawing for comment or construction. In between the meetings, a flow of telephone calls, faxes, posted drawings and letters provided a medium for co-ordinating minor procedural details between the ORGANISATIONS.

[218] Informants noted that when multiple organisations were co-located (as in a previous project), these patterns of communication differed substantially.

Members of the different ORGANISATIONS would meet at these regular and pre-designated times to discuss the state of the building and problems encountered in the design process. These meetings often lasted several hours and were used to reach agreements on undecided details of the design and to partition responsibilities for particular parts of the project between the ORGANISATIONS. An agenda would be posted to the participants before the meeting, and minutes circulated afterwards. These documents set the underlying structure to the solution of the design problems: queries would be noted, transformed into actions and assigned as responsibilities for particular people or ORGANISATIONS. At subsequent meetings, these items would be checked to see if they had been completed.

Through discussions with the other project stakeholders, ideas were clarified about how to generate a design, drawing information from the client and architect about their expectations, and relating these to the site conditions, materials and other resources available. These meetings were generally scheduled (up to a year in advance) on a weekly or bi-monthly basis, with exceptional problems requiring meetings to be arranged when necessary (an unusual phenomenon, and not observed in fieldwork). Many such meetings were observed, each relating to different aspects of the project, known as 'Project Team Meetings', 'Site Progress Meetings', 'Design Progress Meetings', 'Design Meetings', 'Mechanical and Electrical Meetings' and 'Lighting Control Meetings'.

Informal communications, other than the formal meetings between the stakeholder ORGANISATIONS, almost universally involved telephone conversations; these might be combined with a fax, to transmit spatial information, which could then be discussed verbally. Faxes were mainly used to transmit spatial information, or tables of written information too complex to be read out aloud. Telephone communications were almost always brief, except on occasions when the participants were unable to meet face to face. The purpose of the calls was usually to discover information, or to update people on minor changes. Telephone calls were also used to arrange meetings to discuss complex problems, to allow other people to enter the dialogue, and so that the participants could 'communicate more naturally' (informant's words).

A third form of communication between the ORGANISATIONS involved the transfer of design representations, in the form of artefacts. These generally involved paper documents (text or drawings), but in some cases (between the architect and BEG) as computer models on floppy disk. These formed an important, but separate and more formally managed, component to the communications documented above. These documents took several forms, indicating the status of the representation (for

comment or finalised), and which could be critically examined to see how it matched the expectations of the different groups.

Where the design stepped through the various stages from specification towards a final solution, there was a formal, explicit transition, marked by the completion of finalised drawings and other documents; these included the architectural drawings, co-ordination issues, drawings for comment and drawings for construction. Once each stage had been completed, new developments could be built on the back of these prior decisions taken. However, whilst these stages appeared to be discrete units in the design process, they occasionally had to be modified in the light of changes to these completed stages. In addition, some errors, omissions and ambiguities meant that what appeared to be firmly specified was discovered at a later date not to be. Changes also occasionally had to be made as legislation, financial or physical constraints became clear. It was at these transitional stages that informants noted that particular care had to be taken so that minor changes would not cause drastic knock-on effects throughout the rest of the design. The formal documentation was therefore a means of drawing a line under work that had been completed, and returning to change these stages was only permissible if major problems occurred in the design. Change to the completed design after one of these transitions could result in a financial penalty for the ORGANISATION that requested such a modification.

The end result of the meeting or meetings between the BEG engineers and other stakeholders would result in the creation of a ‘drawing for comment’ by the BEG. The ‘drawing for comment’ would be the first externally available (outside the BEG) unified representation of the proposed design. If no comments were made about it, the drawing was ‘passed’ by all of the stakeholders. In any other eventuality, the design would go through another cycle (or more), as it was modified to incorporate the comments made by the stakeholders, before being resubmitted.

The final outputs of the structural design phase for the Roman’s House were the finished drawings, agreed upon by all of the parties involved, and stamped ‘for construction’. These were sent by the structural or M&E team leaders to the construction company to use in the next phase of the design cycle. This ended the BEG’s responsibility for that design problem. However, as the BEG was involved in many such design problems in the project, the designs created could have repercussions upon other design problems in the construction project that they would have to resolve.

## B.4 Features of design in building engineering

### B.4.1 Inter-organisational activity

During the process of design, many documents passed between the engineering designers, and then out to the architects, clients, contractors and other stakeholders; in return, there was a mass of incoming communication which had to be channelled to the appropriate people. Each individual had their own responsibilities for particular components of the project and (should) know of the lines of reporting and responsibility for this. To enable this to be done unambiguously and to avoid contradiction, the BEG had set this out formally in a quality assurance system (QA). Document control was an important factor in the QA process to ensure that duplication did not occur, and that only current documents and designs were in circulation. The QA system specified the forms of artefacts to be used within the BEG and these were rigidly adhered to. However, there was less control of the use of artefacts between ORGANISATIONS, leaving more scope for misunderstanding and confusion. This was a problem for the project, as out of date drawings were said to be occasionally used in error.

The informants noted that one of the reasons that so many lengthy formal meetings were required between the BEG and the other ORGANISATIONS on the Roman's House project was that the site was distant from the offices of the BEG. The telephone was too unnatural and clumsy (informant's description) a method for communication and the site took a long time to visit (half an hour). Due to this distance, engineers tended to try to do as much as possible without having to ask minor questions, something that was not conducive to a smoothly integrated design process. Projects where all of the stakeholders were co-located were seen as the best way of improving the design in a project. Unfortunately, this was unfeasible in relatively small projects for BEG, such as The Roman's House, where the same engineers were working on a number of different design projects.

### B.4.2 Patterns of communication

Formal engineering design processes were defined in the quality assurance system, which specified how the engineering designers were to operate. However, the QA system was not applicable to all situations, and only proscribed methods to be used in the transitions of documentation relating to the design process. Whilst the project related documentation formed a major component of communicative activity and as a mechanism for co-ordinating the design activities, the documentation did not comprise all of these activities. The QA system was therefore not used in the

management of moment by moment, ad hoc interactions, either between the engineers within the BEG, or between the BEG and other stakeholder groups.

Paperwork for the project was maintained in the dayfile. All letters and other information relating to the project sent to or from the BEG were entered into the Roman's House project dayfile, maintained by the mailroom and locally, by the secretary. All incoming correspondence (generally letters and faxes) was entered into the dayfile and a copy sent to the recipient. The team participating in the project had to sign the dayfile on a daily basis and initial the documents directly relating to themselves to demonstrate that the material had been read and understood. This was intended to increase information related project awareness, although in reality, it created a new problem by making too much information available for the engineers, resulting in information overloading. Comments were also occasionally written onto documents in the dayfile, such as 'problem resolved', followed by a date, or possibly referring the reader to a subsequent document or drawing.

Informal, socially mediated mechanisms of co-ordination were managed on an ad hoc basis, in the naturally arising interactions of the collaborating engineering designers. These included the passing of sketches and memo's between themselves to compare their conceptions of the developing design. In addition, perceptual monitoring was used (particularly within the designers at the BEG), as people's physical actions could be observed and the artefacts of work (such as 'desk litter') were visible, making the other co-located designers aware of the activities being performed and the decisions being made.

### B.4.3 Artefacts in the design process

A wide range of design artefacts were used in the building engineering design process, many of which appear to be universal across various engineering disciplines. The artefacts described below were used extensively, both within and between the teams in the BEG, and between the stakeholder ORGANISATIONS.

The most obvious part of the design process was the construction and use of drawings. Several hundred drawings for the project existed, often in multiple copies, and these would be frequently updated. These drawings littered the workplace, often several layers deep on desks; in conversation, the words 'design' and 'drawing' were often used interchangeably, denoting the importance of the drawing to the design activity. However, the physical nature of the drawing was observed to fulfil a number of functions. Whilst the drawing encapsulated many of the features of the design, the representational form of the drawing on paper also allowed it to be manipulated and communicated in a way that an abstract representation of the 'design' could not.

Throughout the BEG and other ORGANISATIONS, various forms of drawings existed, representing the design at particular stages. These drawings symbolised several different meanings, and changes to the form of the drawing often denoted a transitional change in the state of design process. Particular forms of drawing denoted problem ownership, or a change in the status of the design process. For example, the architectural drawings were the property of the architect and were used to communicate the final architectural design to the other stakeholders; signatures and stamps on the drawings also denoted who had assumed ownership of the design and who to query if problems had arisen.

The drawings could also be marked and annotated; indeed the drawings on the engineers desks were usually covered in various colours of highlighter pen, identifying the changes that had to be made to them. They were also sketched and written onto, both for personal benefit and to pass on to others. When talking to the other designers, these drawings would be opened up and gesticulated at; comments made in the meetings were occasionally written directly onto the drawings. When it was not possible to have face to face meetings, the drawings could be faxed (after being photocopied and 'shrunk') to the recipients. These drawings would occasionally be annotated and faxed back (with a resultant loss of quality). Drawings were however, too slow to produce in meetings: as a consequence, they had to be prepared in advance of the meeting and changes distributed after it. On one occasion in a meeting, a drawing was forgotten: the meeting was postponed until it was fetched several hours later. Perhaps surprisingly, sketches were infrequently made, possibly because they were unofficial and did not form a part of the systematic, quality assured, design process. This may account for why that they were rarely used as an enduring artefact in design.

The drawings also embodied the mathematical calculations ensuring that interactions of the component parts had been checked: this would be evident on the status of the drawing, denoted by the stamps on it (e.g. 'for comment', 'for construction') and the initials of the senior engineer who had checked it. The drawings were also occasionally annotated with a comment about the calculations, or with a file reference where they might be found. An 'eyeball check', or comparison of the drawing (mapping onto two dimensional reality) to the engineer's prior experience of such a form to see the plausibility of its structure, was also described as a frequently used check on a drawings validity.

The design of the building within the BEG lay in the CAD (computer aided drafting) system. This CAD model formed an internal computer representation of the developing design. The model could be viewed on screen, or printed out as a drawing

(the only form of output used by the engineers). The models were maintained and created by the CAD operators under instructions from the engineers. Interestingly, the engineers rarely used computers; it was not that they could not, but because they did not need to, this being performed by the operators.

The walls of the BEG and the other stakeholder offices visited were covered in pinned up drawings and other printouts or computer generated images of the design. In meetings, these would be constantly referred to, pointed at and compared to other artefacts. They appeared to provide a common, visualisable object to which people involved in the design, but with different skills and perspectives, might gain a common understanding of the problems being discussed. In the office of the client, a two metre high model of the completed building had been created, and in meetings, speakers would occasionally get up and point to the locations that they were talking about, moving their hands as if they were twisting parts of the structure to a different angle or 'dragging' a part of the structure to another location on the model.

Email was used extensively within the BEG: it was considered to be a useful mechanism for communication because it was easy to generate information for sharing, by allowing information to be forwarded electronically to other relevant parties, rather than circulated as paper copies. It also acted as a 'personal bulletin board' to remind the other engineers about meetings, events and other activities. However, this did intrude into the domain of QA, and because these electronic documents were not (QA) controlled and had no legal basis, email did not have the same significance as the drawings or paper documentation in the dayfile, and was not subsequently used to discuss design related details, only to the *processes* of design, such as proposing dates for meetings and to say when they were going to be away from the office, to which the same ORGANISATIONAL significance was not attached.

Many forms of artefacts were used in the design process, as aids to the individual, as devices for communication and as a means of organising the developing design representations. These artefacts included the drawings (of various kinds), the CAD system, a scale model, the dayfile, a mailing system, a range of annotation and marking tools, desks and walls to pin design representations onto, paper duplication and shrinking technology (photocopier), communication technologies (telephone, fax and email), and calculation tools. Maintaining control of these artefacts was critical in ensuring that only the appropriate documentation and design artefacts were in current circulation. This was a major problem with the project because the engineers became buried under the bureaucratic residue of the communication and artefact control systems, and the work activity became as much one of system maintenance as of design itself.