INFORMATION FLOW IN ENGINEERING COMPANIES: PROBLEMS AND THEIR CAUSES

Claudia Eckert, John Clarkson and Martin Stacey

Keywords: Design teams, design information management.

1 Introduction

Providing everybody with the right information at the right time is one of the greatest challenges facing all organisations. This means providing relevant information and the right amount of information – not too little, but also not too much, so that the receiver does not get swamped in information, unable to tell the important from the insignificant. This paper reports on observations of how failure to achieve appropriate information flow in large-scale engineering design processes contributes to a variety of problems for designers and decision-makers. Our observations support the conclusion that large organisations need to support both personal contact and informal channels, and thought-through mechanisms for information transmission between individuals and groups who usually have little personal contact.

2 Some characteristics of large-scale engineering design

Information management in large-scale engineering design is difficult and challenging for a variety of reasons. **Diversity of channels.** Information is exchanged among humans, between humans and computer systems and written records, and increasingly between different computer systems. CAD models and other documents often play important roles in structuring and coordinating product development activities [1]. **Scale.** Complex engineering products are developed over several years in teams of dozens or even hundreds of people with very different backgrounds and expertise, often working in different locations. For example the design of a passenger aircraft takes over 100,000 person-hours. Large organisations and complex teams almost inevitably have a complex managerial structure with hierarchies in each field of expertise, and specific process management in addition to the business and financial management that all large organisations have. Engineering companies are usually embedded in a supply chain, and need to manage the interaction and information exchange between collaborating companies. They must often follow procedures requested by their customers while enforcing their own procedures on their own suppliers. **Variety of perspectives.** Most design projects involve the collaboration of engineers from different fields, as well as scientists, mathematicians, computer programmers, product designers, CAD-engineers, draughtsmen, technicians and model builders. These different specialists all have their own sets of concepts for understanding the characteristics of designs, and their own way of thinking about problems – what Bucciarelli [2] terms *object worlds*. They have different ways to express ideas, and different skills for creating and interpreting diagrams and other visual representations [see 1]. Communication between object worlds fails to convey the sender’s entire expert understanding, but the receiver can recognise implications invisible to
the sender. It may also require active translation. **Uncertainty.** Design by its very nature is the creation of something new that has not previously existed – this involves a high degree of uncertainty. Initially many aspects of the design are unknown and others are imprecise or provisional. Often many blind avenues are pursued as the design develops. Communicating incompleteness, imprecision and provisionality is an important part of team designing [3, see 4, 5]. Tone and phrasing in conversation can convey uncertainty effectively [6], but sketches and other visual representations carry such meta-information inadequately [7, 8]. **Cost-benefit mismatches in communication through documents.** Computer support for information management has been the subject of intensive research and is increasingly important in industry, but so far the human computer interaction of most engineering support systems has been treated as secondary to the functionality that they can offer. So recording information beyond that absolutely necessary requires too much effort; and the person responsible for recording information is typically not the person who would benefit from the information once it is recorded. Moreover, communication through electronic and paper documents is limited by the expressive power of the available representations [cf 1, 8].

Designers are still reliant on human guides to the huge amount of information potentially relevant to each design, especially for explanations of context. For instance March [9] found in a study in Rolls Royce that designers gained 82% of their information from people they knew and 9% from people they didn’t know. Only 9% of all information gathered by his subjects came from computers (3%), bookshelves (2%), filing cabinets (2%), desks (1%), or drawing vaults (1%).

### 3 Methods

The research reported in this paper draws on case studies in two large UK engineering companies. In both studies we interviewed senior engineers and engineering managers in semi-structured interviews lasting about an hour. In Spring 1999 we interviewed 23 engineers in a large aerospace company in a study focusing on the processes involved in customising a complex product [10]. In Autumn 2000 we interviewed 15 engineers in an automotive company to gain an insight into planning behaviour at different levels of the company hierarchy and the communication problems that result from it. Both studies also investigated communication and information flows, actively exploring issues raised by earlier research on design teamwork [such as 1, 3] and by the communication problems that we have observed previously in a large ethnographic study of the knitwear design process [8]. As these case studies were primarily based on interviews, the results presented in this paper are based on the participants’ own analyses of the communication process. Care was taken in the interviews to establish each interviewee’s background and perspective (which is inevitably biased); and assertions were cross-checked with other interviewees to establish the generality of issues, and whether the different participants had compatible views of shared problems. Some important aspects of collaborative designing, such as how the form and content of graphic representations influence communication, can only be investigated effectively in observational studies. These are planned for a later phase of this research.

### 4 Perspectives on communication

In understanding communication in large-scale design processes, we need to balance and integrate two contrasting perspectives: how individual human beings exchange information in particular interactions; and how information is handled on a larger scale by an organisation.
4.1 Understanding is actively constructed

A number of design researchers with a sociological perspective have drawn attention to how information is expressed and constructed from content and context [3, 2, 6, 1]. They see designs as generated in negotiation between human actors, where information is actively communicated and actively made sense of. Each individual’s understanding of the design situation is dynamic and unique, and is constructed largely through interaction with other people and with all sorts of textual and graphic representations of design information.

Successfully constructing an understanding of what to do in a new or changed situation, such as a modification to a design, comprises obtaining the information needed and making sense of it. Making sense of what you see or are told has three aspects (that are inseparable in practice) shown in Figure 1: interpreting this information from the form in which it is represented; integrating it into one’s understanding of the situation by elaborating it and evaluating its quality with contextual knowledge; and inferring its implications for one’s own tasks and responsibilities, and how to apply it. This necessarily involves learned interpretation skills, background knowledge and awareness of context, which are different for each participant. A representation of design information might be incomplete, ambiguous or inconsistent, or obscure aspects of the design. Missing information must be filled in from context, typically with conventional assumptions or default values, which might or might not be right for the problem. If the recipient realises that the information is incomplete or inadequate, he or she will try to find the missing or correct information, either by going back to the person who has provided the information or by looking for other ways to find it.

![Figure 1. Recipient’s Perspective on Information Transmission](image)

4.2 Information flow

To understand design processes we need a broader perspective than cognitive or sociological insights into individual designing episodes can give us. We need to understand how many different activities fit together to create a design. Taking an information-centred perspective allows us to consider how designing activities are structured by the design itself (as well as requirements and constraints it must meet) and by the social organisation of the designers and their environment. However, information flow isn’t smooth or infallible or confined to formal channels, or even deliberate communication; it is often chaotic and cannot entirely be predicted. In engineering design, a great deal of information is usually communicated through the representations in which the design is generated, such as CAD models or sketches,
whether they serve as focus for discussions or are generated and read at different times and places [see 1]. CAD models, drawings and formal documents are seldom produced to convey specific points. Often they carry more information than needs to be communicated at a particular time. Much information is transmitted through the customary organisational communication patterns, for example distribution lists, between people with particular organisational roles. Designers also become aware of information that they are not actively seeking through the activities of their colleagues.

In taking an information flow perspective, this paper concentrates on communication between the members of a large team designing a complex product, who cannot all meet frequently or solve problems by interactive negotiation (see [11] for a discussion of different communication situations). Even when designers can meet and discuss, they may be responsible for generating and passing on information about particular aspects of the design. A lot of design research has looked at joint designing in meetings, both because it is much easier to study experimentally, and because many important decisions are made in meetings [3, 2]. Tracking information flow in detail through such interactive joint designing is both infeasible and unnecessary for guiding the management of design communication. What is needed instead is understanding what information and expertise should inform joint designing.

5 Manifestations of communication breakdown

The following list does not present a complete picture of possible failures of information transmission. Instead it describes manifestations of inadequate information flow that have been commented on in our interviews or observed in other studies.

5.1 Not understanding the big picture

It is extremely difficult for an individual designer to fully understand a complex product or the process by which it is generated. The designers in our study had a localised knowledge of the product and the process, but had very little understanding of other aspects even on a very high level. For example the aerospace designers had only the most cursory understanding of the role avionics played in the overall craft. Of course, complex products are decomposed as far as is possible into modules with relatively simple interactions, to minimise the complexity of the design process. But lack of awareness of interactions between components of designs and between design processes results in a number of problems, when designers don’t know what information they need to provide at which time; nor what information they need to request.

1. **Lack of awareness of tasks that need to be done.** Team members were not aware of the requirements of other designers and therefore failed to do tasks. Often they knew about big tasks, but small seemingly insignificant tasks can have a huge impact on the design process if they are not done in time, for example ordering a vital component for a prototype.

2. **Lack of awareness of information history.** Team members often don't know where items of information such as specifications and parameter values come from. In consequence they can't trace them back the designers who are responsible for them, and so can’t question the information. If the designers need to change previous decisions such as parameter values, they don’t know who has based their decisions on this value and therefore would need to change their own areas of the design. Tracking information is especially difficult across organisational barriers.
3. **Lack of awareness of how information is applied.** Team members often don't know how their contribution fits into the overall process. They don't know who depends on the information that they are creating, nor how they use the information. In consequence designers often don't provide their colleagues with all the information they need to have, especially about what decisions are provisional, or the boundaries within which parameters can be changed [see 5].

4. **Lack of awareness of changes to processes.** Design processes are often changed because new requirements are added, or scheduled tasks have failed and need to be repeated or replaced with more complex procedures. News of process changes is often not passed on to members of the design team, so that they don't re-plan their own activities, or do tasks that are no longer required.

5. **Missing information provision**

Problems often arise simply because designers are not told what they need to know.

5. **No feedback on information provided.** Team members often don't get feedback on how their information has been used by colleagues. In consequence they can’t identify failings in how well they perform their own tasks or how they communicate with their colleagues, so can’t improve their performance. They may also feel under-appreciated.

6. **No status information.** Team members can often not make sense of the status of the information that they receive; for example if a parameter value is a final value or a simple estimate, or if an element of a sketch is an important and carefully thought-through element of the design or merely a placeholder there to make other elements of the sketch comprehensible [see 4, 7]. People therefore often assume that values are exact and put great effort into meeting a seemingly exact target. In our study of knitwear design [7,8] we found that technicians often ignored parts of garment specifications because they could not assess which aspects they should rely on.

7. **Power structure excludes viewpoints.** Contractors and suppliers are often excluded from decision-making processes, because they have no official standing in the company hierarchy or because the information discussed in meetings is considered confidential. Yet their tasks depend on decisions made in these meetings; moreover the success of the product might depend on the decisions made in these meetings drawing on their expertise and addressing their concerns.

8. **Information is consciously withheld.** Contractors or suppliers are consciously not given information that might be useful for their tasks, because it is considered confidential. Information can also be withheld when the provider of the information does not understand why the information is required or believes the recipient has no authority to know. Henderson [1, p. 65] was often not given technical information as a technical writer, because engineers and administrators could not see why she needed to know (she received much more cooperation when introduced as a sociologist).

5.3 **Information distortion**

In complex organisations information is often passed on via several other people before it reaches the recipient. The generator of the information may not know the ultimate recipients at all, or does not know the recipients’ needs, tasks and background, so can do little to ensure accurate transmission.
9. **Information is oversimplified.** Due to the sheer volume of information concerning a particular design, complex information often needs to be simplified or abstracted to be communicated clearly. However different team members may have different criteria for what information is relevant [see 1, p.157], so significant details and qualifications can be left out.

10. **Chinese Whispers.** Information that is passed on through other people is likely to be distorted. Unless everybody knows the context, the details or emphases are likely to be changed. This applies in particular to information passed on orally.

11. **Hierarchical Communication Paths.** In many companies, communication between experts of the same speciality in different teams is passed on along hierarchical paths. An individual engineer alerts his group leader, who passes information on to his boss outside the particular project, who in turn passes it on the team leader of another project. Information might be passed on through six or eight different people, if there is no horizontal communication between people solving similar problems. Each person selects information as it is passed on, and relatively little information reaches its final destination.

12. **Expertise of Intermediary.** The people who pass on information might not have the technical knowledge to understand the implications of the information, or to argue the case for a particular technical solution. An extreme example is that project presentations to the board of directors or to clients are often made by managers or finance experts with very little technical understanding.

5.4 Interpretation of representation

The representations designers use to express design ideas and other information, and the representation-understanding skills they possess, have a powerful influence on design communication [see 3, 1, 4, 7]. The following two points are taken from observational studies and have not been commented on directly by our informants in the two interview studies.

13. **Interpretation of ambiguous information is based on context.** Information is often presented ambiguously or can be interpreted in more then one way. (Note that any level of abstraction can be fleshed out in different ways, without having being represented ambiguously.) The recipients interpret this information based on their own experience and context, which will not be exactly the same as the originators’ [8, 3; see 4, 7].

14. **Recipients are unable to extract the required information from the representation.** Many kinds of information can be displayed in a variety of different ways, some more effective than others. And many representations of designs make some aspects of the design explicit and hide others. Information can be obscured by the representation, for instance when parameter values have to be inferred rather than read directly. A representation can be vague or ambiguous to someone lacking its creator’s diagram-understanding skills [1], or be incomplete when its creator thinks it is complete.

6 Factors contributing to communication breakdown

Communication problems are seldom moncausal. Communication breakdowns can result from a combination of several problems; so resolving one issue in isolation may be insufficient. For instance, our study of the knitwear design process found a communication bottleneck caused by technicians doing detail design interpreting incomplete and inconsistent
specifications according to their own experience [8]. A variety of cognitive, social, organisational and cultural factors contribute to the problem; Eckert [8] argues that the key issues are the difficulty of creating consistent and unambiguous representations cost-effectively, and failure to recognise difficulties as stemming from communication problem. Bucciarelli [2] points out that interaction and communication across different object worlds (the sets of objects, attributes and relationships that people with particular experience and expertise think with) is always potentially problematic. In our study in the aerospace industry we found that mapping problems are amplified the further the other object world was away from the designers’ own experience. For example the stress engineers and mechanical engineers who work closely together could make reasonable sense of each other’s assertions, while neither group had any understanding of the constraints and needs of avionics specialists, with whom they rarely interact.

In our interviews designers have commented again and again on the importance of personal connections and informal communication. People who have once worked together, for example for the same past employers, talk to each other. People moving between departments often create links between those departments; for example if a load expert is moved to the stress department, he will think about the load implications of his stress analysis. Suppliers are often a conduit of information between competitor companies. Contractors move between different companies in the same industry; while they are bound by confidentiality, they transfer the approach to solving problems from one job to the next. Not surprisingly, communication works best when people can meet each other easily. Communication on the same site will always be easier than between different locations, though technology supporting remote meetings with shared workspaces is proving effective in commercial use.

7 Conclusions

Communication can fail at every stage shown in the figure. Many problems simply arise from information about the product and the process not arriving at the right person in the right way. In other cases designers do not have the background information to make the right inferences from the information that they are given. Our studies highlight the importance of minimising distortion, by ensuring so far as possible that information is conveyed by people who fully understand it, and that information can be traced back to its sources. They reinforce the well-recognised finding that one key to effective knowledge management is enabling the people who have the knowledge to talk to each other.

Ensuring the accurate and timely delivery of appropriate information is a less tractable problem. In complex processes information flow is always problematic and difficult to support. Only if designers know where information is coming from and where it needs to go can they communicate effectively. We are working on tools for planning and managing dynamic design processes [12] based on the parameter values exchanged between tasks, and developing visualisation techniques for design process that make these dependencies and connections salient [13].

Acknowledgements

This research was funded by the EPSRC Rolling Grant to the Cambridge Engineering Design Centre. We are grateful to our informants for the time and trouble they took talking to us.
References


Dr Claudia Eckert and Dr P John Clarkson
Engineering Design Centre
Department of Engineering
University of Cambridge
Trumpington Street
Cambridge CB2 1PZ
Phone: 0044 1223 332758
Fax: 0044 1223 332662
Email: {cme26,pjc10}@eng.cam.ac.uk

Dr Martin Stacey
Department of Computer and Information Sciences
De Montfort University
Kents Hill
Milton Keynes MK7 6HP, UK
Phone: +44 1908 834936
Fax: 0044 1908 834948
Email: mstacey@dmu.ac.uk