Information Seeking and Sharing in Design Teams

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ABSTRACT
Information retrieval is generally considered an individual activity, and information retrieval research and tools reflect this view. As digitally mediated communication and information sharing increase, collaborative information retrieval merits greater attention and support. We describe field studies of information gathering in two design teams that had very different products, disciplinary backgrounds, and tools. We found striking similarities in the kinds of information they sought and the methods used to get it. For example, each team sought information about design constraints from external sources. A common strategy was to propose ideas and request feedback, rather than to ask directly for recommendations. Some differences in information seeking and sharing reflected differences in work contexts. Our findings suggest some ways that existing team collaboration tools could support collaborative information retrieval more effectively.

Categories and Subject Descriptors
H.3.3 [**Information Storage and Retrieval**]: Information Search and Retrieval

H.5.3 [**Information Interfaces and Presentation**]: Group and Organization Interfaces – *collaborative computing, computer-supported cooperative work.*

General Terms: Design, Human Factors.

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1. INTRODUCTION
Designing a new product is intensely collaborative. Design teams create new information – the product design – through exploration and analysis of an information space in a social context [2]. This information space is not a coherent collection readily available to the designers; finding and sharing the information needed to define their product is part of a design team's work. In this paper we examine how two design teams sought information and how they shared the retrieved information within the team.

We define collaborative information retrieval as the activities that a group or team of people undertakes to identify and resolve a shared information need. Information retrieval involves identifying an information need, formulating a query, retrieving information, evaluating it, and applying it to address the need. Collaborative information retrieval involves these same activities but also includes communicating about the information need, sharing the retrieved information within the team, and coordinating the constituent information retrieval activities across multiple participants.

Most information retrieval research and information retrieval technologies are focused on the individual information seeker, not collaborative information retrieval. Because most of this research is based on a cognitive approach, it can provide few insights into the study of collaborative information retrieval. For example, Dervin [5] and Belkin [3] maintained that the need to search for information is a result of some deficiency in a person's cognitive state. Dervin defined this deficiency as a gap that one has which prevents a person from making sense of the surrounding world and Belkin identified this state as Anomalous State of Knowledge (ASK). Taylor [20] decomposed the development of an information need into a sequence of four cognitive states. While these cognitive models guided research in human information behavior, their applicability to either the design of information systems or to the study of collaborative information behavior, rather then personal retrieval, is not obvious.

Only recently have researchers begun looking at information retrieval as a collaborative activity. Studies in military command and control [19] and medical [15, 16] settings have found that seeking and providing information are tightly integrated activities. These studies emphasized the flow of information within teams, building on previous research showing that sharing information within a team is essential to a team's success [10, 18].

Viewing a design team as a social unit, we may ask how it accomplishes collaborative information retrieval. Like an individual,

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the team must recognize its information needs, formulate queries, retrieve information, evaluate it, and apply the results to address the initial need. Each of these information retrieval activities could be performed collaboratively or individually. Information needs may arise through group discussions or be identified by an individual such as a team leader. The task of finding the information may be allocated to an individual or team members may work together to formulate queries, retrieve information, and evaluate it. Applying the results in a team environment may also require disseminating the information to all team members.

This paper describes field studies of collaboration information retrieval carried out by design teams at two companies. The research itself was conducted collaboratively by researchers in information retrieval and in computer supported cooperative work. Our collaboration influenced the theoretical perspectives, methodology, and analyses. In the sections that follow we begin by describing our research methods. Then we describe the context in which these teams sought information, including the purpose and structure of the teams, which is central to their information needs. We also describe how members of each team collaborated with one another and with people outside the team, because these interactions are the means by which information is retrieved collaboratively. With this context in place, we focus on how the members of each team collectively seek information from outside the team and share it with one another.

2. FIELD STUDY METHODS

The research methods integrated approaches from information retrieval and computer supported cooperative work. The work analysis framework of Rasmussen et al guided our analysis of information needs [6, 12, 14, 21]. The framework was developed to help information system designers analyze and understand the complex interaction between the activities and organizational relationships and constraints of work domains, and users' cognitive and social activities and subjective preferences during task performance. It provided the basis for the structure and formulation of interview questions.

We worked individually or in pairs at each site. We first interviewed the team leader about the team's goals, objectives, and organizational context. Then we observed and recorded meetings, interviewed team members and people who worked with the team, monitored group email communication, and observed members at work. We interviewed most team members twice, first asking general questions about their work, its organizational context, the decisions they make, the information they seek, and their work with other people; and the second time focusing on specific information-seeking events. We gave each team member a structured notepad on which to take notes about their information needs, how they searched for the needed information, and the results. In the second interview we asked them to describe these events in detail. We also shadowed and recorded a designer for several hours. All interviews, team meetings, and the shadowed work activity were transcribed and analyzed.

We also asked team members to report the frequencies of their communications with each other and with people in related organizations. Their responses were summarized in communication network diagrams.

3. THE TEAMS

We studied a software design team at Microsoft and a hardware design team at The Boeing Company. Both teams were engaged in product development, not research. Team boundaries can be ambiguous. We focused on teams formally reporting to one manager, which proved to be workable but less straightforward than anticipated.

3.1 Software Design Team

The Microsoft team was designing a web-based help and support service. The team consisted of a manager, a program co-coordinator, two senior product designers, two junior designers, one visual designer and two usability engineers. The service they were designing would provide a unified portal to a wide range of product support information, much of which already existed in separate systems – for example, local application help, windows updates, and product support. In addition, the system was to be extensible so that third parties could add and integrate related content and present it to users in a unified form.

Our study was conducted during months two through four of a twelve-month project. During the observed phase of the project the Microsoft team focused on the functionality and user interface of the service. They sought information about the content that would be included in the service and the ways that content might be used.

3.2 Hardware Design Team

The Boeing team was designing an airplane system in collaboration with a major supplier. The supplier designed their part of the system to meet Boeing's requirements, and the Boeing team designed the interfaces between this system and all other systems on the airplane. The team designed the structural and spatial properties of every interface component, including the spatial properties of the installation and removal procedures for these components. The interface components were acquired from other smaller established suppliers. Some components were readily available as standard parts. The suppliers manufactured new components as specified in the designs and shipped them to Boeing where they would be assembled.

The team consisted of a team leader, eight engineers and two technicians. The engineers on this team had 5 to 20 years of experience in mechanical engineering, and most of their experience was on the same system for other airplane models. Each engineer was a focal for one or more of the subsystems that make up the system design, with responsibility for all the design issues related to that subsystem. For example, there were focals for the fire detection subsystem and for the anti-ice subsystem.

The design of this hardware system required much more time than the software design we studied at Microsoft. Iterations are much more costly and time consuming for hardware than software, and consequently the hardware designs were subjected to thorough analysis before implementation. Our study was conducted during months 9 through 18 of a 36-month design and development period. In this interval the team performed the detailed design of many components. They negotiated and specified the interfaces of many components with their major supplier, created detailed representations of components in a computer-aided design (CAD) system, and provided component specifications to other suppliers.

4. INTRA-TEAM COLLABORATION

Team members worked together to understand their product requirements, create designs, and analyze alternatives, and collaborative information retrieval was part of all these activities. Recognition of an external information need (e.g., undocumented product requirements or the capabilities of an external product

supplier) often arose while team members collaborated. Some of their collaborative activities were initiated for the purpose of getting or disseminating external information. This section summarizes how the teams communicated, shared information, and coordinated.

4.1 Software team

Each of the nine team members had a private office on a common hallway. Much of their intra-team communication was via e-mail. They went to other team members' offices to talk about something critical or exciting, but email was the preferred mode of communication. They rarely used the phone and could not converse while at their PCs, but they frequently interacted in meetings, during lunch, in the hallway, and in their offices. A usability engineer noted the value of oral communication:

"If it's my team, my best method is to walk down the hall. And that would be more in depth; I would get less ... that's where you get sometimes the more emotional part of it, the passionate part of it, the less formalized. If you send email you tend to get specific information points."

While working toward a common goal, each team member had unique responsibilities determined by their job title and experience. This division of labor was central to the coordination of their work, including how they collaborated in information retrieval. The division of labor determined whom they asked for information and to whom they offered information. It also enabled team members to perform some of their work alone, including some information retrieval activities.

The team leader played a central role in coordinating the team's work, and an even bigger role in coordinating with people outside the team. She recruited members, negotiated their roles in the design process, maintained the project schedule, and met regularly with senior members of the team who acted as leads, directing the work of the others. With this pivotal communication and coordination role, she frequently identified information retrieval needs and determined how they would be resolved.

The team held a weekly staff meeting that also served to coordinate their work. All team members heard what the others were doing and planning to do. These discussions helped them know about and recognize the responsibilities of all the other team members. They discussed new information about the team's overall responsibilities in these meetings. These discussions included the impact on current and planned work and led to task assignments.

Some of their work was schedule driven, although the schedule did not dictate their day-to-day activities. Team members worked on the aspect of the system for which they had responsibility. Because of interdependencies among their responsibilities, a deadline for one person often induced deadlines and information needs for others, establishing a temporal cycle of information flow [15]. For example the visual designer, who wished to drive the team's collaboration by proactively producing designs and soliciting comments from other team members, found his work often driven by the needs and schedule of usability engineers:

"To date it's been … date driven. I've been more in a support role for the product designers in usability testing. For example, the product designers and usability engineers will say, 'we're going to do a round of usability testing, we need to know this information by this date.' So I will go and do my design work and provide it to them by the date they need it so they can go and do the test…. So now we've just entered into another stage where we're going to be a little more proactive with the visual design… We're actually going to start providing direction and saying, 'the designs that we do are actually indicative of where we're going and the final product…' I'm actually going to be providing direction and saying, 'Here's how we're going to do this,' and providing a lot of proactive solutions and getting feedback and driving things."

Despite the interdependencies in their work and their frequent communication about the work, team members did not consider their work to be collaborative. Much of it was performed individually or in subgroups of two or three people. One designer noted that the only decisions made by the team as a whole were where to go to lunch and what to call themselves. The team did not make design decisions collectively.

4.2 Hardware team

The leader of this team participated in the preliminary design and specification of the hardware system and had led the design of this system for other airplanes. Before the team was formed, he developed a work plan that detailed the components to be designed and the time and effort required to design them. When this plan was approved, he recruited his team, mostly composed of engineers who had worked on the design of this system for other aircraft.

All eight engineers performed essentially the same work but on different subsystems. They designed the physical structure of every individual part comprising their subsystem and described how the parts will be installed and removed for maintenance. The parts designed and provided by their major supplier and all the parts this team designed had to integrate with one another and fit into a constrained space. In addition, they sought ways to reduce the weight and cost of the subsystem while maintaining the very high levels of reliability required of all commercial airplane systems. Meeting these goals and constraints required collaboration with people outside the team.

The physical work environment differed from the private offices of the software team. This team was located in relatively Spartan office space above the manufacturing floor for their system. The team leader, most of the engineers, and both technicians occupied a single open bay where they could (and did) talk to one another without getting up from their chairs. Not surprisingly, most of the communication within the team was oral, and they used email to distribute documents and for communication with people outside the team.

As noted earlier, each engineer was a focal for one or more subsystems, but in some cases another engineer had more experience and expertise on that subsystem. After years of working on the same subsystem, they had negotiated assignments to different subsystems in order to broaden their knowledge of the total system. One engineer with 10 years of experience was an expert on Subsystem A but focal for Subsystem B, which was the team leader's domain of expertise. He reported, "I consult with [the team leader] on the design on a regular basis about 'what if I did this, what if I did that, what do you know about this?'" He, in turn, mentored an engineer with 4 years of experience who was the new focal for Subsystem A. This engineer reported, "I was sitting right next to him, which was invaluable help. There would have been a lot of things I would have missed, just little things as you go along, little decisions that you have to make. I could just turn to him and [ask] 'should I do this or that or what do you think about that?' And he'll give an opinion, and its immediate feedback, and it really helps."

The team coordinated its work through constant communication, by following the planned schedule, and through use of their design

tools. The work schedule planned by the team leader strongly influenced the team's work, collaboration, and the flow of information. He had developed this plan to meet the overall schedule for this new airplane, and they all recognized the importance of meeting their schedule. The two technicians on the team helped engineers stay on schedule by contributing to the detailed descriptions or CAD models of their parts. All the engineers and technicians created their designs using the CAD system, which stored all the models in a database. Using a program called FlyThru, they could visualize all the designed parts in a given volume and determine how well they fit together.

5. EXTRA-TEAM COLLABORATION

Both teams performed only part of the work required to produce a finished product. Here we consider how they worked with other people who participated in the development of the product. These other people were often the sources of information the team turned to when resolving collaborative information retrieval needs. Through collaboration, the teams knew whom to approach for information, and the information provider understood the teams' contexts and shaped the information to fit their needs.

5.1 Software team

The team we studied was responsible for designing the end-user functionality and the look and feel of a new web-based service, but they would not provide the service content or write the production code. Program managers in another team specified the requirements, obviously a major influence on the design. A team of developers would ultimately determine what functionality was implemented. A testing team would ensure that the product functioned as planned. The content providers authored the help and support material that was to be integrated in the new portal. The design team, program managers, developers, and testers were all part of the same organization, whereas a different organization provided content.

Inter-team coordination was a major source of tension, requiring substantial attention from those in leadership roles. Members of different teams came from different disciplines and had different perspectives and motivations. One designer noted that his focus was on how the product should be experienced by users, the developers wanted to write "really cool code," and the testing team wanted them to create products that were easy to test.

The boundaries between team responsibilities were not always clear. The team leader saw the relationship with the content providers as problematic, because the content providers wanted greater authority over the design than she was prepared to offer. The team needed and requested information from the content providers about their plans and requirements, but the team found the response too constraining.

"And then we've also had a lot of problems, I don't know if it's really a constraint, but with so many content providers working with us, we've had problems with … them giving us a little too much feedback. It gets to be hard, because [we] are always trying to make decisions about whether we should take that feedback, whether we should ignore that feedback. We try to listen, but we don't always want what they have to say, and it's complicated . . . there was a lot of times they would approach us and almost make it seem that we had to do what they said."

The team leader strove to manage extra-team collaboration. She stated, "I feel like my job is mostly to go and get X person to talk to Y person, to make sure that whatever it is gets closed most of the time." She ensured that communication flowed between her team and everyone else involved in the product, and she was responsible for coordinating with everyone else. Meetings were one of her tools for managing this communication. For example, she noted that the content providers often went to a program manager regarding design issues instead of coming to her, and she did not like that. She established a weekly "brainstorming meeting" for her design team and the content providers in order to manage communication with them. She also attended the program managers' meetings and invited them to her team meetings.

In addition to these managed communication channels, team members worked individually in their area of specialization with people outside the team. For example, the visual designer provided designs directly to members of the development team who, in turn, implemented the designs for the usability tests. Designers complained that the requirements specifications often were unavailable or incomprehensible, and they contacted the program manager directly for clarification. Occasionally, team members communicated with people in their discipline located in other parts of their company about tools and methods, forming a community of practice.

5.2 Hardware team

The hardware team worked with many other specialists to determine the final design. The team never had meetings limited to the team members but met frequently with other people. The team focused on the structural and spatial properties of their components, and other specialists focused on other aspects of the design. For example, a stress analyst approved every component, indicating that the components had the strength required to meet their operational requirements. A thermal analyst informed the team of the temperatures that their components would experience. A materials engineer advised them about the properties of alternative materials. A manufacturing engineer and a factory representative advised the team about problems that might be encountered when assembling or maintaining the components. Two engineers provided computing support, managing all the data produced by the team. These and other specialists were invited to a weekly Design Build Team (DBT) meeting where everyone discussed the status of the system and any related issues. Talking about these meetings one engineer noted, "That's the whole goal, is to get feedback, to get problems identified before it's too late."

In addition to these DBT meetings, every engineer collaborated with people from these other disciplines. In contrast to the Software team, these engineers viewed their work to be inherently collaborative. One engineer noted,

"Even our designs in some ways are a team decision. I mean we get manufacturing to give us some comments. We may not all get in a room and do it all at once, but we try to review it with suppliers and manufacturing and the mechanics and maintainability and all those different groups… And of course stress, but then we also, we also get our materials experts to review what we've done and make sure we're using materials that are good for that environment. So, we get a lot of people involved in it."

The team also collaborated with people at supplier companies, again through both meetings and individual interactions. They held weekly teleconferences with representatives from their major supplier, and they held other teleconferences as required with other suppliers. These collaborations appeared to be the most stressful and challenging aspect of their work, and they took steps to make them more effective. For example, they systematically prepared a formal

description of every interface between their major supplier's parts and their parts. They wrote drafts, sent them to the supplier for comment, negotiated agreement, and tracked the progress of each instance of this process until they had reached agreement.

The problem, of course, is that the high degree of communication within the Boeing design team could not be achieved with the supplier's design team. One engineer explained that the supplier

"…had to introduce two new [parts] in an area that is already packed full of Boeing hardware. We are struggling with it, because they're trying to come up with design solutions independent of us, unfortunately. We'd like to be a part of those studies, and not being collocated between two companies, it's a difficult thing to do. So they're back there working on a design, and they complete it and throw it over the fence to us, and then we say, 'well, that's fine and dandy, but we've got problems here and here and here.' So it's an iterative design process, rather than a collaborative one."

6. COLLABORATIVE INFORMATION RETRIEVAL

We defined collaborative information retrieval as the activities that a group or team of people undertakes to identify and resolve a shared information need. Both the software and hardware teams sought information central to their products (such as requirements, designs, and analyses) and information about organizational issues. Although the products they were designing were entirely dissimilar and their tools and disciplines were dissimilar, there were striking similarities in the kinds of information they sought and the methods they used to get that information. In this paper we focus on the common strategies and methods used by these teams to acquire information.

6.1 Software team

6.1.1 Discovering information needs

Team members discovered information needs while working alone, in small groups, and in meetings of the whole team. While working alone they frequently discovered that they needed information to continue their design. For example, in thinking about an upcoming test, the usability engineer needed to know the company's perspective on "software as service." A designer planning to use pop-up screens for explanations needed to know the average length of such explanations. Sometimes team members recognized new information needs while in a meeting or when talking to other people, whether team members or outsiders. Sometimes people outside the team, such as a program manager, alerted them about information they would need that they had not anticipated.

Some designers explained that much information they needed to do their individual design work did not exist. They needed information about the constraints on the design, a clear understanding of "what to build," detailed requirements, production schedule, and information about the types of users to be served (novice, beginners, expert). Because the project was in early design stages it was very dynamic and most specification documents were not final. Therefore, the designers had to talk to those who were supposed to provide the information and "help" them define answers.

Team members identified their information needs in various ways. At times, email or face-to-face communications preceded a meeting in which an information need was discussed. Other times, the manager, a team member, or a program manager raised an information need for discussion during a meeting. To obtain a shared understanding of an information need, individuals sometimes met with the manager or among themselves. Sometimes, achieving a collective understanding required lengthy discussions. For example, the team once considered several alternatives in parallel in order to continue their work without obtaining the information that would enable them to constrain the set of alternatives. In preparation for such discussions, the team might invite a person who could have the information to try and understand the need and find an answer at the same time. At other times, however, there was no need for the team to negotiate a shared understanding: the need was clear to all team members the moment it was identified.

When the team identified an information problem, it often delegated one team member to find and report the information. This allocation of responsibility was usually guided by the expertise of the person and by the information resources, including people, that person knew.

6.1.2 Design proposals as queries

Several team members explained that it was often difficult to obtain information from other people about specifications they needed for the team's design work. A strategy they developed to get this information was through a process of feedback elicitation. In this process, the team members disseminated ideas or documents representing a proposed design for the sole purpose of receiving feedback from the people who could give the team the needed specifications. This feedback included the information the team needed to have. The most experienced designer maintained that this was the best strategy for obtaining information. He explained that the successful designer could not simply wait to be told what to do or what the specifications were. The designer must tell others what he or she would do and convince others to engage.

Thus, asking for feedback was a method to engage the information source into giving the information. It should be noted that most often the information source did not have the information until she or he was engaged to create it. For example, a designer might need to know what color to use for the screen's background. It was likely that the person charged with this decision had not thought about it. Asking for this piece of information was not likely to encourage him or her to make a decision and create the specification. Faced with a design proposal in which the screen color is, say, pink, would invigorate the person to react to the proposed design and determine the screen's color.

This strategy was widely used in different contexts. Several team members explained that they tried to distribute their ideas or documents to a large number of people so the team could get maximum information. Such ideas and documents could be put on the Web or in a text document. Some such documents were sent to the people who were supposed to provide the information, and others were presented and discussed in meetings with such people. For example, at one staff meeting the team presented a mockup of the interface to the program manager and the content providers to get information about how the content was structured and what were likely topics and subtopics.

Although an individual team member often presented the documents or ideas, preparation usually involved a collaboration of several team members. In these instances the team collaborated in the query formulation phase of information retrieval.

6.1.3 Retrieving information from people

Formal publications and websites provided some of the information needed by the team, but people were the primary source of

information sought collaboratively. Some team members specifically noted that they did not use formal information sources. A usability engineer was the only team member who described the use of formal sources in detail. When he had an information problem he first turned to published reports, whether internal or external. For example, he consulted a repository of Microsoft usability reports that was searched by keywords. When these sources failed to provide the needed information, he tried to find a person who had done related research.

Several team members explained that they preferred to contact people directly. When asked where he gets the information needed for his work, one designer responded, "I guess there are some documents, but there's never enough information in the documents so you have to go and speak to the person who wrote the document. Again, they haven't always sorted out the answers, so again the information isn't always there. That's kind of the trick, I guess, to keep talking to people and gathering information."

All team members agreed that asking people directly for information provided benefits beyond simply obtaining an answer to their question. The team leader explained that getting information through direct questioning is faster than other methods, and furthermore, "you get what's important and their little analysis of it." She wanted some interpretation, not just the fact. The visual designer saw other benefits: " . . . it not only builds relationships in the company, but also people may have had experiences that I didn't even realize and just kind of mining for information that way, and also networking . . ." The usability engineer valued the information he received from people because it was less formal and included the emotional and passionate parts of the information. In addition, he explained, "If you send email you tend to get specific information points. Sometimes I'm looking more for the experience, looking for a larger picture of things."

Although obtaining information through direct contact with people was most often an informal process, the formal structure of the organization helped identify whom to contact. Several mentioned seeking the person responsible for a particular aspect of a product when they needed information related to that aspect. To identify such a person required familiarity with the organizational structure, which was dynamic and complex, and was, therefore, not straightforward. One approach was to identify possible candidates, then ask a manager above them whom to contact. Team members who were relatively new to Microsoft were less likely to use such strategies and relied on advice from their manager, mentor, or from managers of other units whom they knew.

Finding people through other people was not reserved to new employees. All team members constantly sought recommendations for experts to contact. At times, team members accidentally encountered such recommendations when talking with other people. The usability engineer, for example, talked with his carpool partners, and they had recommended promising contacts several times. Finding information about such contacts was also the purpose of networking. Team members built their networks within the organization so they could turn to them for advice.

Almost every meeting we observed included at least one instance in which team members asked for help in identifying the right person for the information they needed. At times, the collective knowledge and experience of the team was enough to identify that person; at other times, the team had to turn to another person for help. Meetings with the program manager were particularly useful in this respect, because he knew many people who were related to the product and worked with other units. In addition, team members used more formal sources to find experts. They posted requests for advice on listservs and turned to other people in the organizational hierarchy who were qualified to provide an answer. Sometimes, individuals provided the information, rather than a contact for the information, in response to such requests. When a designer, for example, asked where he could find answers about some issues relating to the updates, the PM promised to contact the people who had the information directly and bring the answer back to the team.

6.1.4 Information seeking in group meetings

For relatively complex information needs, the team or a subgroup of the team invited an information source to a meeting. The team leader frequently invited information sources to team meetings. For example, information exchange was an important component of regularly scheduled meetings with the program manager. The team expected him to inform them about new developments related to the product on all administrative levels. The team leader also invited representatives from the content and the development side of the product to provide information the team needed. In addition, selected groups of team members initiated and participated in meetings with the program managers, developers, and content providers about information needed for their specific design tasks. The two visual designers, for example, met with the development team to understand what they needed to support usability testing.

Another strategy to obtain information was to participate in meetings of other teams. The designer who had been with Microsoft the longest considered such meetings the main place where he got "really good, valid information." Other team members did not often adopt this strategy, but they had fewer connections with people in other teams. The usability engineer mentioned that he went to quarterly usability meetings. Clearly, participation in meetings of other groups was easier for team members who had a well-established network within the organization, a network that could inform them about these meetings.

6.2 Hardware team

6.2.1 Discovering information needs

As in the software team, the engineers frequently discovered that they needed additional information to design the parts. Typically, the engineers began their designs by looking at designs of existing similar aircraft. Then they considered how they could improve the design, possibly reducing the cost or weight of components. Before embarking on these revisions, however, they needed to know about constraints the new design would have to meet. They needed to know whether other engineers were working on components in the same area, constraining the space available to them. They needed to know about non-spatial constraints, such as the stress and thermal conditions that their components would encounter because these factors influence the choice and thickness of materials. They also needed to know about constraints that influence assembly and maintenance of their components. This information was not available in any documents or repositories. It was only available from specialists in stress, thermal properties, and the manufacturing and maintenance processes.

The team as a whole discussed their information needs in DBT meetings, and often the people who could fulfill their needs were present at these meetings. The meetings generally focused on the future, looking ahead to anticipate and avoid problems. In the early phases of their work, the meetings focused on their work processes.

They needed information about schedules and procedures. For example, they needed to know when their supplier expected information about some of their components. They needed to know how to calculate the costs of test hardware. They considered how to work with one of their smaller suppliers.

When the engineers began to complete their designs, they needed to know whether these designs satisfied all requirements. Would the designed part be strong enough, how much would it weigh, and how much would it cost to manufacture? Did anyone have ideas about ways to improve other attributes of the design, such as ease of maintenance? Experts provided definitive answers to some of their questions. For example, the stress analyst calculated the strength of the part, and the materials expert provided information about weight. To answer other questions, they presented their designs in review meetings where everyone could offer their analysis and suggestions.

6.2.2 Design proposals as queries

As in the software team, a common strategy for obtaining information was to request feedback about a design or part of a design. The engineers presented the complete but not finalized designs of their parts in regularly scheduled DBT meetings. The attendance at the DBT meetings was much greater when these designs were presented. It seemed that everyone wanted a chance to comment on the design before it was finalized, and many useful suggestions emerged in these meetings. In the first such meeting, for example, the factory representative suggested a change that would make the part easier to install.

The strategy of requesting feedback was not reserved for meetings. When considering a design change, engineers asked more senior members of the team for advice. They produced two-dimensional pictures of their preliminary designs and showed them to the factory representative or specialists. In some cases they sent pictures to their major supplier for comment.

6.2.3 Retrieving information from people

Because most team members were collocated in the same room, they could easily ask one another questions throughout the workday. Some engineers were focals for subsystems that had been designed for the predecessor system by other engineers on the team. While considering how to improve the older design, engineers often asked their colleagues for advice or for the rationale of their design decisions. They also talked about how their parts would fit together.

Finding the person with knowledge about a design decision was not always so easy, but it was the only source of that information. While reusing information in a prior requirements specification one engineer decided he needed to understand its rationale and contacted the original authors.

"So we had to go through and specify all these things, and I looked though some of the requirements, and I said, 'gee, this doesn't make sense. Why did they do this?' So, I spent a couple days hunting down various people that had been involved with the spec ten years ago and said, 'well, do you remember any of this? Well…I think we did it this way.'"

Early in the project this engineer proposed that the team record its rationale while designing the system, but this was received with little enthusiasm. Others observed that recording rationale would add to their work load, and there was no way to ensure that future design teams would even know that this documentation existed.

The likely source of needed information was defined by roles and responsibilities on the system development team. The stress engineer would answer questions about the stresses that a subsystem would encounter and whether a specific design was sufficiently strong to withstand those stresses. The thermal engineer would answer similar questions about temperature. The engineers could walk down to the factory, just below their office, and talk to the factory representative about installation issues related to their system. Asked whether they talk to the shop floor staff, an engineer said, "Yeah, exactly, what they've had problems with, or you show them a little picture...does this look reasonable? Does this look like something that you'd have a problem with? Yeah, we do that all the time. Just try to keep from adding new problems to the design."

6.2.4 Information seeking in group meetings

The most common place for generating and resolving common information problems were the weekly DBT meetings and the meetings with suppliers. One engineer was responsible for the agenda of the DBT meetings. When issues required the presence of people who were not on the team, or were of interest to other people, he invited them to the meeting. In one instance, he invited a Designated Engineering Representative (DER) to tell them about formal requirements. A DER is a highly trained engineer who represents the Federal Aviation Administration (FAA) and interprets FAA regulations. They had just learned that their system would experience greater stress in this new higher performance airplane, and some design changes would be required to compensate. The DER helped them understand the design consequences for their major supplier and for their own designs. This example highlights the important role that people play in communicating the requirements for an airplane and its systems.

Many of the items on the DBT meeting agenda were information needs. Usually, the team discussed the situation and either got answers at the meeting or devised a plan for finding what they needed to know. The team would then decide whether to keep the item on the agenda for the next meeting. This was done in a systematic manner. It was not unusual for an information item to be on the agenda for several consecutive meetings.

Obtaining information from their major supplier was more difficult, and meetings were one vehicle for obtaining this information. They held weekly teleconferences in which they systematically worked through lists of issues. For example, they documented all the interfaces between their parts and the supplier's parts, and they expected the supplier to review, negotiate, and finally approve all these documents. These agreements were essential because they could not complete a design if the interface had not been resolved. They repeatedly asked the supplier for information about their progress reviewing each one of these interfaces.

6.3 Summary of collaborative information retrieval strategies

These teams were similar in the kinds of information they sought and their strategies for acquiring it. Both teams collaborated in every phase of information retrieval: identifying an information need, formulating a query, retrieving information, evaluating it, and applying it to address their information need. They also communicated about their information needs, shared retrieved information within the team, and coordinated the constituent information retrieval activities across multiple participants. This section summarizes our observations regarding each of these activities.

6.3.1 Identifying needs collaboratively

Individual team members of both teams sometimes identified team information needs while working alone and brought these needs to the attention of the team through email (at Microsoft) or conversation (at Boeing). Team members sometimes brought or raised a question in a meeting, such as how test hardware costs will be covered, and the teams pondered and discussed, recognizing that they lacked the information needed to answer the question and deciding how it should be resolved. Some information needs arose in team meetings or in ad hoc group discussions. Sometimes a person outside the team, such as the software program manager or the factory representative, brought an information need that the team took on.

6.3.2 Formulating queries collaboratively

Both teams sought information about design requirements or constraints, and a common strategy was to solicit feedback to a design or design concept. We view the design or concept as a query intended to elicit information. Individual team members worked alone or in collaboration with one or two colleagues to create these design queries. The software team included groups of two who worked closely together to design their products, and in the hardware team technicians often helped engineers produce CAD models. Query construction is likely to be more collaborative when this strategy is applied in areas with less specialization than technical design work. For example, the software team leader solicited input from all members of the team when formulating presentations to management, and these presentations could constitute another form of query.

6.3.3 Retrieving information collaboratively

The most common sources of information were people closely associated with the design teams. For the software team these sources included the program managers, content providers, and developers. For the hardware team the key sources were regular attendees in their DBT meetings. We can view these information sources as members of larger teams that included the design teams. In fact, this was the accepted view at Boeing, where the larger group was called the Design Build Team, and it in turn was viewed as part of a much larger Systems Integration Team. When team members were asked to list the other members of their team, they frequently asked us which team we were asking about. The team boundaries are fuzzy [11], and collaborative information retrieval by a team often involves retrieving information from a member of a larger team.

6.3.4 Communicating about information needs and sharing retrieved information

Meetings were the setting for collaborative information retrieval by both teams. As noted, team information needs were often identified and analyzed in meetings. The teams collectively decided how to resolve the information need. One strategy was to invite someone to a subsequent meeting to talk about the information they needed. People were a primary source of information for both teams, and in a meeting they could concurrently acquire the information, disseminate it to the team, and explore related issues interactively. The meeting also provided a forum for evaluating the information and determining how to apply it.

6.3.5 Coordinating information retrieval activities

Coordinating the information retrieval activities was rarely a challenge for either team. Individual team members readily accepted information retrieval tasks related to their existing team responsibilities. For example, one engineer acted as the weights focal on the hardware team, and when an issue arose in a meeting about weights, he was assigned to find the information and report to the team at the next meeting. Team leaders generally took responsibility when higher levels of management were the likely information source or when relationships were strained with the information sources, such as the content providers for the software team. Team meetings also contributed to coordinating these activities. Team members accepted responsibility for information retrieval tasks in meetings, and these tasks were tracked on the meeting agendas of the hardware team.

7. IMPLICATIONS FOR COLLABORATIVE TECHNOLOGIES

Commercially available information retrieval tools were designed to support an individual seeking information. These tools provide little if any support for collectively identifying information needs, collaboratively constructing queries, or disseminating the retrieved information. We began this research hoping that we would discover behavioral patterns that could provide a foundation for more effective support of collaboration information retrieval. We found, instead, that information retrieval by design teams is not a holistic activity. It is embedded within their work activities, and any of the constituent activities may be performed individually, in ad hoc groups, or in meetings. At this point we can offer only a few suggestions regarding ways that information technology could better support collaborative information retrieval. Planned detailed analyses of individual information retrieval events such as [7] may provide additional guidance regarding potential technology requirements.

A common information space is a central element of many collaboration systems [1, 4, 16, 17]. The common information space consists of a repository with features intended to help teams find, organize, and manage their shared information collaboratively. These repositories are particularly important for geographically distributed design teams [13]. Some common information spaces (e.g., BSCW, eRoom) are intended to support generic teams, and others (Nexprise Program Manager, PTC ProjectLink, EDS TeamCenter) are intended to support product-development teams. These technologies generally include tools for searching, sorting, and filtering the shared repository, facilitating access by any member of a team to that team's information.

How would such an information space support collaborative information retrieval as practiced by these two design teams? While collaborating in the shared space, team members could recognize an information need and use the features of the space to discuss it and decide how to resolve it. They could assign the retrieval task to a team member as an action item and track its status. Because the information is not part of the team's shared space, the assigned team member must search for it elsewhere and then could add it to the shared space and use notification features to disseminate the information.

The information space could support the collaborative information retrieval more effectively by supporting retrieval from information resources outside the shared space. The search capabilities of these technologies are limited to the contents of the shared space, but they could search outside and pull designated information into the shared space to facilitate dissemination to the team. They could also support searching for people outside the team who have needed

information. It might seem that an expertise location system could support this, but the team member must often find a responsible person or an accessible knowledgeable person, not necessarily the most expert person [8, 9]. For example, a question about material properties should be directed to the materials engineer for this airplane program, not the most expert materials engineer in the company. Team members would benefit from explicit representations of responsibilities and tools for searching these representations.

8. CONCLUSIONS

Design teams have collective information needs that are met through collaborative information retrieval. Seeking and sharing information is an integral part of designing any complex system. Individual designers may have unique information needs that they resolve by seeking information independently. Many of their information needs, however, have consequences for other team members. Any information retrieval activity (identifying information needs, formulating queries, retrieving information, evaluating it, and applying it to address the need) may be performed by an individual on behalf of the team, by an ad hoc group, or by the team working together in a meeting. Technologies intended to support teamwork could be more effective by recognizing and supporting collaboration in the activities that comprise information retrieval and their coordination.

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