TOWARDS INFORMATION EXPLORATION SUPPORT FOR ENGINEERING DESIGNERS

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ABSTRACT

Modern engineering design often requires localization and utilization of many heterogeneous information sources. In concurrent engineering this becomes even more complicated due to the many different approaches and expertise involved. Information localization and utilization activities are complex and only insufficiently supported today. This paper reports from a case study addressing information exploration aspects of a large engineering design project. The aim was to investigate what information the design engineers used when carrying out their design work, how they used the information, which sources were accessed and how the designers get access to the information. Based on this analysis a first list of overall requirements for how information exploration can be supported by means of computer-based tools is established. Two findings were essential: The most important type of information concerns potential contact persons having specific expertise and knowledge, and the most frequent applied search approach was similarity search, e.g., search for a similar problem, idea, component, type of project, etc. The study, furthermore illustrated that engineering designers' exploration must be supported through a seamless switching between many types and sources of information.

INTRODUCTION

The manufacturing industry is confronted by increasing demands for improved quality products, shorter lead-times, higher flexibility, etc. One answer to this has been to apply the concept of concurrent engineering bringing knowledge of all stages of the product life-cycle—design, development, production, use and destruction—into the early phases. The result is, however, involvement of many people having different competences in the design. Concurrent engineering design thus becomes even more complex. Teams of collaborating actors have to make design decisions which have to be based upon as qualified a basis as possible. In order to do so there is a need for exploring possibilities, potentials, etc. in many heterogeneous sources of information. This is a time consuming and difficult task. This fact combined with the rapidly emerging information super highways (internet, WWW, etc.) makes it highly relevant to discuss what characterizes engineering designers information need and usage, and what kind of computer-based support of exploration activities should be provided. These are the main questions addressed.

Based on a case study of a concurrent engineering team of engineering designers having different background and expertise this paper identifies a set of essential characteristics of the exploration and integration of specialized information from different domains design engineers conduct during their work. This leads to a set of requirements for how these activities could be supported by means of computers.

Much research in Concurrent Engineering, Engineering Design, HCI and CSCW aims at understanding what characterizes design work. Bucciarelli (1984; 1987) has illustrated the general need for thorough studies of engineering work. Others have studied what kind of information designers need in order answer questions about and verify designs (Kuffner and Ullman, 1991), which kind of information classification structures engineering designers should be provided with (Court, 1995), relevant tools and information systems platforms for engineering designers (Blessing, 1995; Govindaraj, 1997), how to provide handbook information (Burns et al, 1997), or which information sources engineers use and how they are used for finding product information (Wall, 1986). Studies of how actors in specific information domains request and search for information (Pejtersen, 1989), and establishing general requirements for how to structure electronic text information (Dillon, 1994) have also been carefully conducted. Our own previous work has explicitly addressed how engineering designers coordinate their distributed collaborative activities (Carstensen et al., 1995a; Carstensen and Sørensen, 1997). Up till now, however, most studies have had an analytical approach aiming at understanding behavior and problems.

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Most of the studies have not been explicitly directed towards actual design of support systems.

First our approach is briefly introduced including a brief introduction of the work setting observed. A set of the most central findings from our field study is described, and based on these a number of requirements for computer-based support are identified and discussed. The paper is concluded with a brief discussion of the requirements and an introduction of our ongoing work.

RESEARCH APPROACH

In order to obtain a coherent understanding of—and to design computer-based tools for—manufacturing, field studies are essential (Keyser, 1992; Siemieniuch, 1992). This paper is based on data collected in an empirical study of one development effort at Danfoss, a large Danish manufacturing company. The company employs several thousand people including large departments of both development and manufacturing. The study mainly focused on which information the engineering designers used in their design work and how they got access to this information. The field study and the preliminary data analysis was conducted over a period of ten months and was exclusively based on qualitative data collection techniques such as qualitative interviews (Patton, 1980), questionnaires and study of project files and documentation. Approximately 15 interviews were conducted by one or two of the three researchers involved in the data collection process.

The research approach used in collecting and analyzing data can be characterized as qualitative research heavily inspired by both Work Analysis (Schmidt and Carstensen, 1990; Rasmussen et al., 1994) and by ethnographic approaches to studying engineering work (Bucciarelli, 1984; Bucciarelli, 1987). The data analysis was based on theories and conceptualizations for work analysis promoted in Rasmussen et al. (1994) and Schmidt and Carstensen (1990). Albeit we call it “ethnographically inspired”, our approach can be characterized as having a structured and targeted orientation. Although we did not start out with a strict set of hypotheses, we did bring an articulated perspective. We explicitly addressed information exploration needs, sources, etc. and analyzed the work according to a number of dimensions (cf. Pejtersen et al., 1995):

- Overall functions conducted,
- The goals the actors work towards,
- The constraints under which the work must be accomplished,
- Prototypical tasks conducted,
- Types of decisions taken by the actors and strategies applied, and
- The information required to accomplish the tasks.

A qualitative approach offers the obvious strength of providing rich and detailed data, enabling a deep understanding of the conditions under which work is performed. It does, however, present a major limitation in terms of promoting statements of general validity. As Mason (1989) argues, the purpose of research must be to provide both the richness of detail and relevance of research problems studied, as well as a certain tightness of control or rigor. We do not believe that one empirical effort necessarily needs to encompass both aspects. We do, however, recognize that since the results reported in this paper are drawn from a single field study, we can neither make claims as to the generality of the findings, nor to a rigorous research approach. The organizational culture at Danfoss favors that work is primarily organized in projects. It is reasonable to assume that the type of project work studied can be made subject to some generalization if an organizational culture of a similar nature is observed.

The engineering design project addressed was finished when we made our investigations. It was therefore not possible to observe the actors while working. All the statements and descriptions in the following are based upon a set of retrospective comments and reflections from the involved actors and on a detailed analysis of the structure and content of the project files. This reduces, of course, the possibility of describing how concrete activities were undertaken.

The work setting

As mentioned, one large engineering design project was studied. The aim of the design project was to design and plan the production of the PVE II, a new and improved version of a controller for hydraulics. This is a small component to be designed into fork-lifts, trucks and similar machinery to control the hydraulically based technology. It consists of a complex electronic structure including a number of chips and flexprints encapsulated by a light-weight plastic house. It is technically a very complex component, and the description presented here is extremely simplistic. It is, however, for the purpose of this paper not considered relevant to describe the component in further detail.

The PVE II project lasted 4 years and there were naturally some changes in the manning of the project. Most of the time about 10 actors were involved in the project. Although they all had a background as engineers they came from rather different departments and had very different expertise, and thus different perspectives on the design to be conducted. The typical manning included the project manager and three engineers from electronic engineering. Apart from these one actor from each of the areas of mechanical design, production planning, quality assurance (QA), marketing and purchase were more or less full time allocated. Furthermore, an expert from a specialist group on environmental protection was involved as an “environmental protection guardian”.

The project manager, the electronic engineers and the mechanical engineer were physically placed in the same room, and the person from the production planning had his office close to. The others had offices in other buildings several hundred meters away.

The analysis presented here is based upon the work of this group. They had, naturally a lot of interaction with other specialists, groups, departments, etc. both internally at Danfoss and with external partners. Three major external sub-suppliers were involved in the project. These were responsible for respectively: 1) Designing a complex and essential integrated circuit; 2) Compiling the electronic components and encapsulating them into one component; and 3) Development of the flex-print technology to be used.

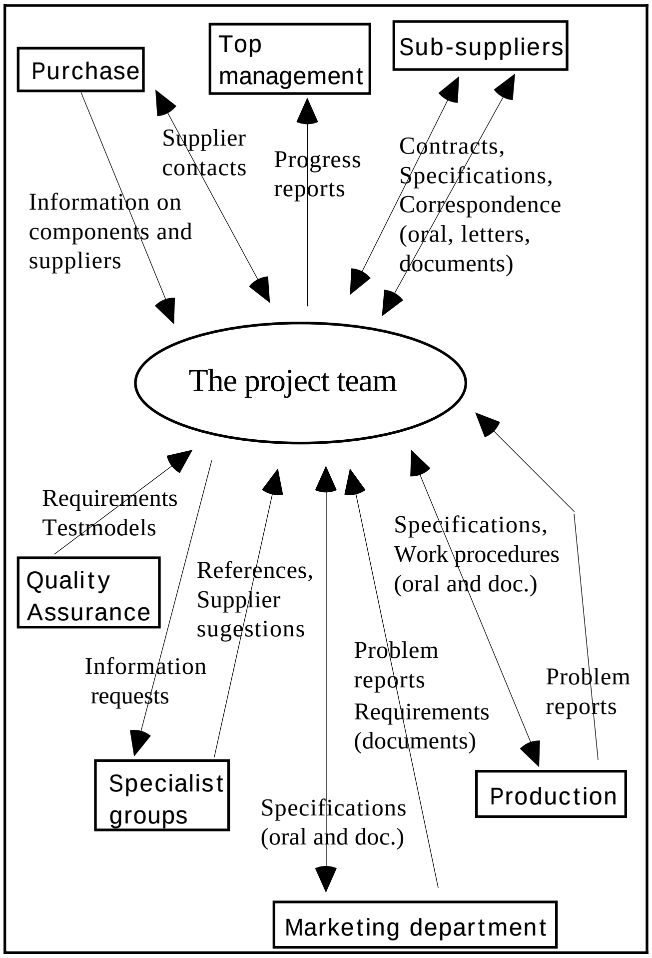

Figure 1: A "context diagram" illustrating the most important interaction between the project team and different stakeholders during the project.

The common field of work for the project team was the requirement specification, design specification, design, performance testing, and production planning of the new improved product. Development projects at Danfoss are partly organized according to a general overall project model: When the ideas, purposes, intentions and possible ways of addressing the specific problem have been investigated a basic specification is written specifying the functionality and quality and time requirements, and who are to be involved, what resources will to be used, overall work plans, etc. This is produced as a collaboration between the project manager and the marketing department. Next, the product is specified and designed, and the required tests are specified resulting in a design and test specification. Furthermore, a production plan specification is produced. When the product design is completed and the first products are produced a product specification specifying the actual characteristics of the finished product is written. This is used as a basis for the sales materials and specification notes produced by marketing department.

As mentioned we explicitly requested the goals, functions and tasks defined and undertaken in the work. Each actor involved in the project had, of course, private and personal goals that might to some extent contradict or conflict with other goals in the project, either other actors private goals or the overall goals within the project. It is out of the scope to discuss these here. We only addressed the project goals the actors, upon request, formulated.

From a management and work planning perspective the goals were formulated in terms of four issues. To

- Design a product having a higher reliability and quality than the previous version and which can be manufactured without increasing production costs,
- Increase the know-how on application of hybrid technologies in Danfoss products,
- Contribute to the general knowledge of and guidelines on development of highly reliable mechatronical products, and to
- Accomplish the project successfully within the defined period of time and by means of the resources specified.

From a technical perspective the goals were related to making as much of the design as possible based on integrated electronic circuits and components which are as reliable and cheep as possible, design and encapsulate the electronics so that it is as resistant to external factors (water, vibrations, etc.) as at all possible, reduce the use of materials (especially materials causing problems for the disposal situation), and ensure that the final product could be produced through effective and efficient production processes by means of production tools that were either existing or fairly easy to specify and design.

ESSENTIAL TASKS IDENTIFIED

To fulfill the goals a long series of tasks had to be planned, undertaken and managed during the project work. The most important groups of tasks were:

Functional specification included collection of requirements for the functionality, performance and resistance to external factors, collection of information on complaints and problems for version 1, and based upon the information specification of requirements for the new product. Two important tasks concerned informing all relevant actors and external partners on the requirements, and setting up the test specifications. All requirements should be verifiable. The choice of testing technique was based upon price, validity, equipment requirements, and how it could fit into the production processes.

Architecture design concerned identifying possible decompositions, selecting among these, and specifying of the chosen. Clear and useful interfaces between the sub-components and easy compilation in the production process were essential evaluation parameters.

Module and components interface design. Based upon the designed architecture all interfaces and interactions between the sub-components had to be specified. This required establishment of a list of scenarios supporting checking that the interfaces covered all possible situations.

Module and component design and implementation. Possible designs for all sub-component and modules had to be identified and described. Considering pros and cons for the different suggestions was essential. To the extent that the designs had implications for other components an important derived task was to inform all relevant actors.

Testing and problem diagnosing included setting up test beds and testing the individual components, modules and the prototypes. A major effort concerned identification of possible causes for the problems, including carrying out sub-tests to identify the causes precisely.

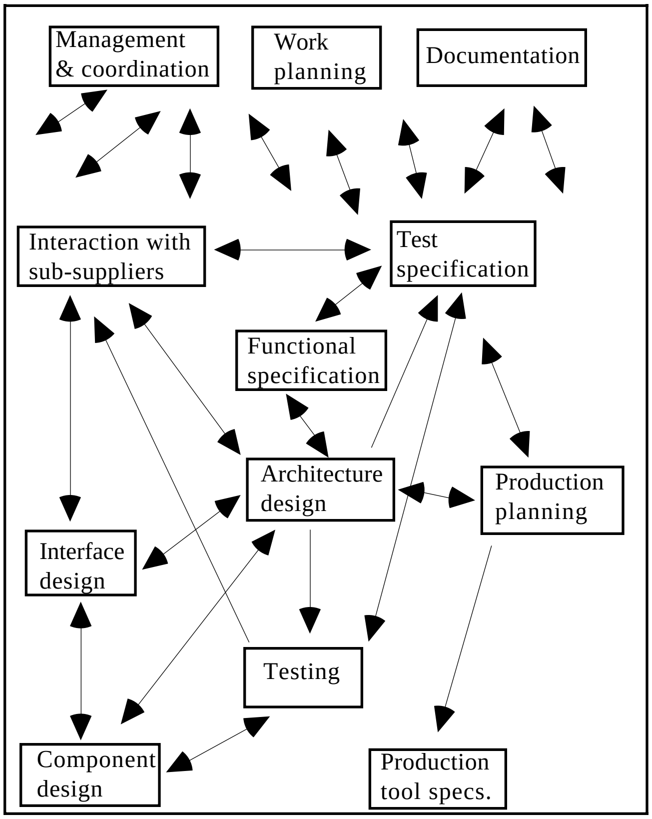

Figure 2: A function model of the work conducted within the PVE II project. The boxes each contains one main function. The arrows between the boxes illustrate that one function provide input for another function. The many arrows from the three function at the top (management, work planning, and documenting) indicates that these functions have interaction with all other functions.

Production planning concerned collecting information about the PVE II, consider how it could be produced and compiled, chose among the possible processes, and specify the selected production process. The selection was influenced by production time, price, and the possibility of designing acceptable work places. Based upon the chosen production processes a set of requirements for production tools was specified, including identification of potential tool-suppliers.

Interaction with sub-suppliers was related to the contacts to external partners. First task was to identify which components that could be designed or manufactured and delivered by sub-suppliers. Then potential suppliers had to be identified and a list of criteria for choosing the suppliers had to be established. It was an important task to handle the contacts to the suppliers and determine the required frames for establishing a fruitful collaboration. Aspects like trust and confidence were extremely important.

Management, coordination and planning had to do with identifying all the tasks to be conducted, relate the tasks to work periods and deadlines, and to responsible actors. The resulting plans should then be distributed to all the actors. Ensuring a proper level of information to all was essential.

Documenting required many resources too. All relevant design decisions had to be documented, the progress and plans had to be specified, all communication and contracts with external partners had to be filed, etc. A basic set of tasks thus had to do with establishing and maintaining a file structure, and filing all documents, drawings, notes, letters, minutes of meetings, etc.

The list of central tasks is by no means exhaustive. The purpose is only to provide an indication of the type of tasks and problems the actors in the design team were confronted to.

INFORMATION USED

To handle all the tasks mentioned the engineering designers requested information on a long series of different topics. We organized these needs according to a number of expertise information areas: Technical; End users; Marketing; Maintenance; Disposal; and Production (cf. Pejtersen et al., 1995).

Technical design information

Technical information covers both information related to electronic design, mechanical design and quality assurance. The information used typically concerned:

- Characteristics and specifications of designs, tests and test equipment, both for previous and the current design,
- Component specifications,
- Standards and norms for hybrid components,
- Potential sources for problems in designs, and
- Methods and techniques for design and testing.

The sources used covered a very broad spectra. The most used sources are specifications from previous designs "having similarities to our design," product and component specification sheets, and colleagues, either at Danfoss or at suppliers. As one of the designers noted in an interview:

> "I usually ask in the group if there are others that previously have had similar problems. [...] We spend a lot of time discussing the things in the group, and we establish small scenarios and experiments to try to provoke the same problems as those others have reported on version 1 of the PVE."

The personal contacts appear to be an extremely essential source for information. Most of the engineers interviewed mentioned that they, when searching for information on a specific problem very often contacted colleagues, people from the consultants department, engineers and technicians from supplier companies, etc. It is more frequent to ask "*who* might know something about this problem" than to ask "*where* do I find information on this." An important source for information on specific products and suppliers is the purchase department (through personal contacts to people in the department). Other sources frequently used were textbooks, CAD/CAM drawings and handbooks. Also the norm-specification produced by the norm-department were accessed regularly.

Another kind of information search was related to the attempts to keep up-to-date on specific topics. Fairs and exhibitions were mentioned as very important sources, both for keeping track of state-of-the-art, and for getting specific information on products problems, etc. Also browsing through a number of the most relevant journals was frequently used. The problem with this is that:

> "There is a lot of stuff that looks interesting, but when I see it I don't know whether I'm going to need it. And when I need it, I don't remember where I saw it and whether it was exactly what I needed"

The strategies for searching information differed a lot and needs further analysis than what has been conducted so far. It was, however, quite obvious that similarity searches were frequent. The opening question was usually "where do I find information on a problem, idea, situation, etc. similar to.."

In the early phases (concerned with establishing ideas) the written sources were considered most useful together with personalized sources, e.g., suppliers or consultants that could provide overview information. Later, the information searches were related to solving specific problems or generating specific ideas or suggestions. Then the personal contact was preferred and the requests were formulated as "who will know something about this?" Hence, the main search criteria was persons with specific expertise.

End user and Marketing information

The end user information concerns information about the future users of the product, their needs, expectations, etc. Marketing information covers marketing aspects relevant to the design. The information covered for example:

- Characteristics of the type of equipment in which the PVE II should be integrated into,
- Known problems in the previous version and the causes,
- Prices and performance of competing products, and
- Design specifications for competing products.

This information were usually collected through direct contacts to the customers, i.e., the companies using PVEs as build-in-components in their product. Access to end-users of these products (e.g., fork-lift drivers) were rare:

> "Only if we have problems and visit the customers of our customers do we get direct access to the end users. Our contact will normally be the dealers selling the trucks and fork-lifts."

The main sources are thus customer companies. Concerning the problems with the existing PVEs the department receiving product complaints at Danfoss was a major source. Another source frequently used was sales material from customers and competitors. However:

> "Analysis of competitors products is important as well, but they represent yesterday's product. This information source is good for formulation of a technical minimum standard, but it is not useful when our task is to identify new needs and new markets."

The strategies for collecting information were usually to visit existing and potential customers. Product requirements, new needs, etc. were then discussed with the customers.

Production information

An essential area to have knowledge and information about is the production processes to be used when the final product is going to be manufactured. The information requested in relation to the design typically concerned:

- Characteristics of the production tools and line,
- Financial aspects of the different tools and lines,
- Different materials implications for which production processes will be possible, and
- Possible work place designs and their implications on safety and job satisfaction,

The main sources to get this information were specifications of previous production line designs, colleagues in other production departments, and colleagues in the purchase department having knowledge about and access to the suppliers delivering production line equipment. For the design engineers in the project the most important information source on production design aspects was, of course, the production planners involved in the project. Again the most frequent question concerned "who".

As for the technical information the major sources for being informed on state-of-the-art were browsing through a number of relevant journals, attendance in fairs and exhibitions and personal contacts to people working with design of production tools. As for the technical information the main strategy followed was to attempt to find information on a situation or problem similar to the one confronted with now.

TOWARDS EXPLORATION SUPPORT

Based upon the characteristics described a number of overall requirements for computer-based support of activities related to information exploration can be introduced. The engineering designers should, of course, be supported in exploring information on the different areas of relevant information.

Types of information

Engineering designers need many different types of information. A computer-based information exploration support system should provide easy access—including seamless switching between use of different search strategies and information sources—to the following types of information:

- Previous designs.
  This should include detailed information on designs that have previously been conducted, both within the organization or from competitors, suppliers, etc. This could typically include requirement specifications, functional specifications, overall architectures, technical drawings, descriptions of methods used, etc. Cross-references between specific aspects from one type of infor-

mation to another should be provided (e.g. between functional specification and drawings). These could for example appear in browsing tools as hyperlinks (cf. e.g., Nielsen, 1990) or similar technologies.

- Design rationales.

  Related to the information on previous designs information on the line of argumentation for the decisions taken in the design could be provided. This should include possibilities considered and arguments for choosing the solution chosen. Prototype tools for tracking the design processes and the rationale behind the decisions exists, e.g., gIBIS (Conklin and Begeman, 1988) or EGRET (Johnson and Tjahjono, 1993). These should be used as inspiration.

- “Similar products.”

  Based on characteristics of the component to be designed (product, instrument, module, etc.) it should be possible to get access to descriptions (similar to those mentioned in the two previous bullets) on components that have similarities with the one to be designed.

- “Known problems” in products.

  The information provided according to the requirements in the three previous bullets must also include explicit descriptions of known problems, weaknesses, etc. in the designs.

- Component specifications

  Access must be provided that allows the engineering designers to browse and search in specifications of components that are considered used in the design. This information browsing should include facilities for searching for component information related to several different aspects, e.g., performance, price, basic technology, supplier, etc. Furthermore, facilities for evaluating a component according to certain characteristics should be provided.

- Standards and norms.

  This should be up-to-date information on the standards and norms for different types of components. This information must include both organization specific standards and norms and national and international standards and norms.

- Working procedures.

  Procedures, standard methods and techniques, etc. defining frames for how the work must be performed, managed, coordinated, etc. should be accessible to all involved actors. This should include both organization specific procedures and general procedures established due to laws and regulations. Information on working procedures must be presented so that it can be compared and related to existing work plans within the concrete project. To support a close collaboration among the actors it is important to have these structures visible and accessible (see e.g., Carstensen and Sørensen, 1997). Several attempts to design computer-based systems providing support for understanding the organizational context exists (e.g., Kreifelts et al., 1991) and can be used as inspiration.

- Production line characteristics.

  Information on production of existing products and components should be available. The requirements here are similar to those mentioned in the three first bullets on previous designs. The information shall include specifications on bill of materials, production tool descriptions, rationales for work place designs, and salary structures.

- New materials and components.

  Up-to-date information on new materials, technologies, components, etc. relevant for the design should be provided for the design engineers. One of the essential research question that must be addressed concerns how to define “relevant”.

- Literature and research results.

  Information on new techniques and findings from research within relevant areas must be provided. This information must be presented so that in can both be browsed as general information and it can be searched for in relation to specific and concrete problems or ideas.

- Relevant persons.

  The most important sources for information are colleges and other actors having knowledge and/or experience on specific topics. Structured and easily accessible information on relevant persons must be provided too. This information can include persons both within and external to the actual organization. Again, this information needs to be available both to very concrete and specific problems or ideas, and as general information on a specific topic. There exists examples in the literature on systems aiming at providing facilities like the one required, e.g., AnswerGarden (Ackerman and Malone, 1990). These need to be tested out in some detail in an engineering design environment.

- Project documentation.

  The previous bullets have listed information that can be considered as external to the concrete project. However, projects produce a lot of information themselves, e.g., plans, specifications, drawings, communication with external partners, contracts and agreements, etc. Access to all information in such a structure must be provided. Support for establishing and maintaining the structure of “project internal” information needs to be provided too. This structure must be visible to all involved actors.

This list should only be considered a first draft of the types of information that must be provided for engineering designers. Further analysis and more detailed descriptions of the required information, how to structure the information, and how to present the information in the use-situations are required.

Requirements for the information access

A central aspect of requirements for support of information exploration in relation to engineering design is, of course, *what* information should be provided. However, another essential problem is *how* to provide access to the information. Five central issues on this will briefly be raised here.

There is need for both getting access to information in situations characterized by needs for very specific and concrete information and a more general overview of information on the same topic. The former will typically be used in order to find information related to a specific problem or question. The latter is related to situations of browsing in order to learn new things and to be aware of the existence of information on this topic. The latter can also be related to search requests like "what do we know about this ...?"

From our investigations, it was obvious that similarity search was the most common type of search. This indicates that our support systems must provide facilities for requesting information like: "give me information on designs similar to this...." The different types of similarity search need to be studied further. There is, however no doubt that this will be an essential requirement for a design explorer support tool.

When searching for relevant information, it is important that the users are not bothered with practical problems on switching between different information sources. An engineering design exploration tool must provide a seamless shift between the different sources, i.e., problems with the different formats, different search machines, different database hosts, etc. should not be visible to the user. The seamless navigation and source shifting can also be supported by means of hyperlinks or similar facilities.

As mentioned in the previous section an often used information access method is to ask "who might know about or have experience with this or that topic?" This type of information access must be supported. This can be implemented by providing access to databases containing person profiles and information on how to get in touch with these persons. It should also be considered to provide facilities allowing actors to raise a question and then more or less automatically getting the request routed to a relevant person. Previous tools providing this type of facilities should be studied further, e.g., Answer Garden (Ackerman and Malone, 1990).

A fifth requirement concerns the (somehow surprising) fact that much of the information stored by engineers is filed by means of chronological order only. According to our studies an understanding of the chronology in the project was also an essential parameter when accessing the files later. This use of chronology should thus be supported by the computer-based exploration tools.

The preliminary requirements mentioned have a number of implications for the technological platform that the support tools are based upon. The general requirements concerns:

- High degree of flexibility in mixing the use of many tools,
- Access across different media,
- Support of converters between different domain languages to bridge the vocabulary problems (Chen, 1994).
- Step-vice refinement of search profiles,
- Similarity search support,

Etc.

It is out of the scope of this paper to discuss these further.

CONCLUSION

This paper has—based upon findings from a field study of a team of engineering designers at Danfoss—established a first list of overall requirements for how engineering designers can be supported by means of computer-based tools. It has been illustrated that the most important source of information is other actors (colleagues, suppliers, etc.) with expertise and experience on specific topics. Furthermore, it has been argued that the most common search type is similarity search, which thus needs to be provided by information exploration tools. The support discussed here concerns mainly overall requirements for computer-based support of activities related to information exploration activities. Citera et al. (1995) investigated how information systems should be organized in order to support collaborating design teams, and their recommendations were quite similar to those presented here.

The requirements should only be considered a first draft of which types of information that must be provided for engineering designers and how this could be done. We need further analysis and more detailed descriptions of the required information, how to structure the information, how to present the information in the use-situations, what information engineers share and how, which mechanisms engineering designers use for supporting their collaboration, and how to cope with the complexity introduced from the fact that collaborating engineers often are physically distributed in time and space.

The understanding and knowledge presented here and in a number of working papers from the Design Explorer Project (DEX) provides, however a starting point for sketching prototypes of systems supporting engineering designers. DEX is a three year cross-disciplinary project aiming at specifying requirements for an information system that will effectively help design team members from different domains and organizational cultures to locate and utilize diverse information sources and interact more effectively throughout the design process. For a detailed description of the DEX project see Pejtersen (1995) and Pejtersen et al. (1995).

We are currently working on establishing a conceptual basis for structuring and organizing the required information, and on developing prototypes illustrating how the information exploration support can be provided by means of the Internet, WWW, and multimedia technologies.

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