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Patterns in design discourse: A case study

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Abstract

Knowledge-intensive CAD must support knowledge building in design environments. Since knowledge sharing is a central activity in the collaborative design process, much of the design knowledge is embedded in the design discourse. For this reason, systematic capture of the design discourse may provide a practical means for knowledge building. This paper presents a case study of a design project and analyzes the discourse to illustrate this point. Our purpose is also to understand characteristics of the discourse in order to support its capture as well as to support knowledge building. The case study is a project that was undertaken by a geographically distributed team, involved a non-routine design problem, and employed several computer tools for team collaboration as well as for specific design tasks. In this paper, we present several quantitative measures for the different types of design information, the use of tools and media, and the role of different types of knowledge in the design process. We interpret these measures in the context of the design project to begin to answer the questions: how could knowledge-intensive CAD have aided in the design process and how can we support building and reuse of knowledge in such collaborative design projects?

Keywords

Design discourse, collaborative design, knowledge building, knowledge intensive CAD.

1 INTRODUCTION

In this paper, we look at knowledge-intensive CAD from the perspective of knowledge building; that is, how design knowledge is constructed and shared in design environments. We propose that

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a design environment should support such knowledge building naturally during the design process, *i.e.*, the task of knowledge building should be as effortless as possible. Our hypothesis is that capturing the design discourse provides a good means to knowledge building. Design is an information and knowledge intensive activity, and in design projects involving several designers, sharing information and knowledge becomes a central task. One can look at a design as the outcome of an argument, as in IBIS (Rittel, 1973), in which designers propose, criticize, refine, abstract, and make concrete ideas and concepts that lead to a final product. Konda *et al.* (1993) argue that design is an activity where designers move toward a shared understanding of the design artifact by negotiation and reconciliation of several different perspectives. All these activities require information and knowledge to justify them, *i.e.*, the discourse consists of uncovering and revealing knowledge relevant to the current design issue. The ability to capture this discourse in appropriate conceptual structures makes this knowledge explicit for future reuse.

Our primary aim in this paper is to demonstrate the knowledge intensiveness of the design discourse and point out that design systems should support growth of such knowledge by systematically capturing and organizing it. Secondly, through a systematic study of the design discourse, we aim to provide a better understanding of the possibilities for supporting knowledge building.

One of the major roadblocks in studying the team design process has been an inability to capture the interactions and exchanges among participants in a design project. In typical design projects, large quantities of information are generated and communicated in the discourse among the design participants. Among these participants are clients (who specify the needs and requirements), designers (who develop a description of an artifact that fulfils the need), manufacturers (who make the artifact) and suppliers (who supply parts or components of the artifact). For reasons arising from the need for efficient information exchange and from the diversity of participants, design information is transmitted in a variety of representational forms (Leifer, 1991). Usually, this cacophony of design discourse goes unrecorded because the focus is on making the artifact and not on documenting the process that led to its creation.

We, in collaboration with our colleagues at Stanford, have created an experiment that has allowed us to capture much of the design discourse. Our experiment involved a design team for the Stanford ME 210 class. The team was composed of three students from Carnegie Mellon and four students from Stanford. Because the expertise required to realize the design was distributed between the two sites, the team found it necessary to communicate frequently. Because most of the communication occurred using computer-based tools, we were able to capture most of the design discourse. In addition, all team members understood that they were to be involved in all tasks and that they were to inform the team about what they were doing. An important characteristic of this study is that the authors were actively involved in the design and manufacturing process, which has allowed reconstruction of missing information from context. As a first step in the study, we have developed rough measures of the information (such as design specifications, artifact behavioral models, and manufacturing information) generated and shared during the design process. We have also developed measures of the use of tools and media (such as CAD packages, e-mail, faxes, and face-to-face meetings) that facilitated the discourse. Collectively these quantitative measures can be used to answer questions such as: what are the types of information (domains of discourse), how does the information focus change (fluctuations in the domain of discourse) and how are the tools used to facilitate the discourse? A second set of measures were also developed to quantify the role of knowledge in design. These measures indicate the influence that different types of knowledge have on design.

This paper presents a detailed description of these quantitative measures, as well as computation and interpretation of these measures for the design project mentioned above. Having provided some rough quantitative understanding of the design project, the paper elaborates the concept of knowledge-intensive CAD by asking the questions: how could knowledge-intensive CAD have aided in the design process? and how can we support building and reuse of knowledge in such collaborative design projects? Finally, the paper presents some relevant questions and research directions that we are pursuing.

2 UNDERSTANDING DESIGN DISCOURSE

2.1 Background

Many studies have been undertaken to understand individual design processes. Among the types of studies are ethno-graphic studies (*e.g.*, Bucciarelli, 1988), verbal protocol analyses (*e.g.*, Ericsson and Simon, 1984) and case histories. Many studies of design processes using these techniques can be found in the literature. Participatory observation studies include Wallace and Hales (1987); they studied the progression of a design and presented both quantitative and qualitative results on measures such as activity times. Fewer studies have been undertaken to understand the information flow in team design. Subrahmanian (1992) and Finger *et al.* (1993) have studied information flows in design processes, however these studies were performed after the designs were complete.

This study is a participatory observation – a type of study in which the observer also participates in the process he or she is observing. The authors have participated as active members of the design team and have also carefully observed and recorded the process. The participatory study provides several advantages when carefully done. First, it provides an opportunity for the observer to understand the process more completely and to ensure that the design discourse is properly documented. Second, during analysis, if information is ambiguous, the observer can resolve it through memory of the context in which the information occurred. However, a balance must be maintained between participant and observer roles.

In this preliminary study, we have categorized types of design information and studied the media by which they are transmitted. We have also provided rough techniques to measure the quantities of information and the use of media. Related studies concerning information measures in the design area where semantics are important include Suh (1990) and Baya and Leifer (1994). Suh has proposed measures of information as required to satisfy functional requirements. In contrast, Baya and Leifer have defined information measures independent of what the information is used for. These measures are much finer than ours, and the focus of their study is limited to one design session to create one design concept by a single designer. The aim of our current study is to categorize the design information generated during the design discourse and provide some coarse measures that reflect the information exchange during the overall design process.

2.2 Goals of the Experiment

The study has two main goals. The first relates to the modeling and use of information in the design project. We are interested in studying patterns in the discourse that took place over four months. These patterns are expected to provide an overall quantitative understanding of the design process including temporal changes in the design focus and in the use of tools, and correlation between the nature of information and the tools/media used to model and communicate it. This understanding is essential for developing and validating design process models, developing information modeling and sharing support systems, and so on. The second relates to use of knowledge in engineering design. We propose to establish metrics to measure the influence of knowledge on design decisions and to provide some quantitative measures. We first discuss these two goals and then provide a detailed description of the results for the design case study.

Quantitative Measures of Information and Use of Tools

In this paper, we will study the following patterns in the design discourse:

1. *Information (domain of discourse)*: What does the design discourse consist of? Can this information be categorized?
2. *Information type versus time (fluctuations in the domain of discourse)*: How does the type of information generated depend on the project status? This measure indicates changes in the information and the knowledge required for the design as the project progresses;
3. *Information type versus media (domain of discourse vs. facilitators of the discourse)*: What media and tools were most useful in providing support for modeling and communicating a certain type of information?
4. *Use of media versus time*: What are the changes in the use of media of modeling and sharing with respect to time? This measure suggests the nature of the processes of knowledge acquisition and formalization during the design process, knowledge sharing and development of shared meaning.

These patterns will be studied in the context of our particular design experiment. For our study, we will look at the following characterizations of the process:

1. *Categorization of information*: The information generated and shared during the design projects is categorized according to its content. This categorization provides a basis to analyze the information;
2. *Medium of modeling and communication*: What kinds of media and tools were used to model the information? What kinds media were used to transmit and share the information among participants? What are the characteristics of these tools (computational capabilities, processing, *etc.*)?

Quantitative Measures of the Role of Knowledge

The role of knowledge in the design process is to transform an abstract functional specification into a concrete artifact description that can be manufactured. In this paper, we identify the role of different types of knowledge in this transformation and provided quantitative measures of the knowledge involved. Specifically, we examine the following measures:

1. *Knowledge versus influence*: What is the correlation between types of knowledge and their influence on the evolution of the design?
2. *Influence vs. time*: How does the influence of knowledge change with time during the design process?

To develop these measures, a categorization of knowledge and metrics for measuring the role of knowledge must be developed within the context of the project. In this paper, we discuss these two characterizations of the cooling system design process. We also present metrics for the interrelationship between time, categories of information and media and tools.

3 THE COOLING SYSTEM DESIGN PROJECT

3.1 Background

The design project, which is the subject of our study, was sponsored by FMC Corporation and involved the design of an innovative cooling system for AC induction motors for use in hybrid electric-drive automobiles. This motor will be used in the Stanford Hybrid Automobile Research Project (SHARP). Due to the demanding functional specifications required by this application, FMC and SHARP believed that a new approach to cooling AC induction motors, involving forced coolant flow through the motor internals, was required. Better cooling would maintain the operating temperature of the motor at a sufficiently low temperature to ensure efficient operation.

The FMC/SHARP project team consisted of seven graduate students from two institutions; three members were located at Carnegie Mellon University and four at Stanford University. The team members possessed varying levels of academic and industrial experience as well as varying degrees of involvement in the project. Due to the initial design project description, team members were selected who had an interest and/or experience in heat transfer and fluid dynamics analysis, and machine design. The duration of the project was five months. Table 1 gives the major characteristics of the project.

Table 1: Characteristics of the design process

Team location and composition	Two teams (3 + 4) - Stanford & Carnegie Mellon Two clients - FMC and SHARP Additional consultants - Stanford & Carnegie Mellon
Domain of the design.	Fluid dynamics, heat transfer, and machine design.
Novelty of the design.	Novel, but constrained by the existing motor design.
Time frame.	Five months. Four months completed. Currently in final manufacturing and assembly stages.
History.	Past two years. A motor with different cooling system has been designed and manufactured.
Nature of deliverables.	Hardware: A tested and functional cooling system. Documentation: Test procedure and results. Design process.
Major design concerns.	Function (cooling). Manufacturability. Testability. Budget and time limits.

Due to the distributed nature of the design team, we recognized early in the design process that we needed to establish a formal communication protocol. We also needed a communication infrastructure to support our protocol. Furthermore, since we knew that a research goal for this project was to study the design process, the communication protocol and infrastructure were designed to facilitate capture of the design discourse. Most importantly, the project members were encouraged to document the process. The distributed nature of the team was exploited to maximize the level of design discourse via the communication protocol and thus to capture the design information. We intentionally divided responsibility for the subfunctions of the design across the two locations (*i.e.*, Pittsburgh and Palo Alto).

In this section we will discuss how we applied a systematic approach to analyze and develop measures for information, use of tools, and the role of knowledge in the cooling system project. We will also interpret these results and discuss their use in understanding the design process.

3.2 Measures of Information and Use of Tools

Categorization of Information

The information generated and shared during the design of the cooling system can be categorized into several types. Although somewhat *ad hoc*, the following categorization provides us with patterns in the discourse that are interesting from the perspective of understanding the design process. Hence, this categorization is used in the rest of our study.

- *Specification information*: information about design specifications, information about the existing motor needed to understand specifications, pointers to information regarding the existing motor, interaction with the client to understand and negotiate specifications, client feedback on progressing design;
- *Function and constraint information*: product specifications translated into technical functions and subfunctions the design should satisfy. Information about establishing these function structures and definition of constraints to satisfy specifications belong to this category;
- *Design solution information*: information about all stages of design (conceptual, embodiment, detail), knowledge associated with evolution of design, arguments for a design solution. This information includes conceptual solutions, rough sketches, detailed fabrication drawings, *etc.*;
- *Behavioral information*: knowledge about physical principles involved in the design (fluid flow, heat transfer, electro-magnetics, *etc.*), analysis and behavioral models (*e.g.*, thermal resistance models), *etc.*;
- *Vendor information*: inquiries seeking off-the-shelf components from various vendors, vendor feedback as to what is available, knowledge associated with these components – how to use their parts, how to modify our designs to accommodate their parts, *etc.* Example components include sealing rings, bearings, grommets and windings;
- *Manufacturing, assembly and testing information*: inquiries and information about manufacturing, assembly and testing processes, suggestions for design modifications from manufacturers, cost estimates, knowledge associated with design for manufacture, assembly and testing;
- *Organizational information*: calls for meetings, agendas, to-do lists, project scheduling, task allocation;
- *Infrastructural information*: information about how to use computer tools for communication, training participants to use the communication and modeling tools, *etc.*

Tools for Modeling and Communication

This section gives a short description of the tools that were used in modeling and communication in this design project. Table 2 compares the tools' support for these functions, as well as comparing the type of information supported by the tool.

Table 2: Tools for modeling and communication

Tool	Concepts/Intended Use	Support for Modeling and Communication	Information Type
WWW	Hypertext concept. Client-server architecture. Supports multiple protocols for information retrieval and transfer.	Modeling is external to WWW. Supports communication.	Limited MIME types defined for text, images, audio, and video.
Hypermail	Creates an archive of hyperlinked documents from e-mail correspondence between group members. Hyperlinks to any other URL can be placed within e-mail.	Limited support for modeling of the design process. Support for communication via WWW.	Primarily text, although images may be included as URLs.
PENS	Archives personal notes. Facilities sharing of information by making them available on WWW.	Limited support for modeling; provides one layer of classification of notes. Support for communication via WWW.	Primarily text, although images may be linked via WWW.
CU-SeeMe	Synchronous-mode video conferencing via the internet.	No support for modeling. Supports communication.	Audio, video, gestures, graphics.
Timbuktu	Synchronous-mode screen sharing and file transfer.	No support for modeling. Supports communication.	Types of data dependent on shared application.
Specific design tools, *e.g.*, MathCAD, AutoCAD, MacDraw Pro.	Specific purposes such as geometric design, cooling system thermal analysis, optics and controls modeling and analysis.	Modeling support for specific purposes. No communication support.	Types of data specific to tools (*e.g.*, CAD drawings for AutoCAD)
Project management tools, *e.g.*, MSProject.	Project tracking and management.	Project modeling. No communications support.	Organizational
Word Processors, *e.g.*, FrameMaker	Detailed progress reports on the design project that capture the details of the design.	No modeling support. Communication support via documentation.	Text and pictures.
Telephones, tele-conferencing.	Speech transmission.	No support for modeling. Supports communication.	Audio.
Faxes	Document duplication at a distance.	No support for modeling. Supports communication.	Text and pictures.
Face-to-face meetings		Some support for modeling. Supports communication.	All

- *CU-SeeMe*: CU-SeeMe (Cogger, 1995) is a video conferencing application from Cornell University developed for the Macintosh. It is a point-to-point video conferencing tool which can also be used for multi-party communication by use of a reflector operating on a separate (Unix) machine. Audio is provided through Maven (an audio-only application) which is integrated into the CU-SeeMe package.
- *WWW*: The World-Wide Web (Berners-Lee, 1994) is a data model developed by Tim Berners-Lee at CERN, which merges hypertext, information retrieval, and wide-area networking. It supports a client-server protocol for information transfer.
- *PENS*: Personal Electronic Notebook with Sharing (Hong, 1994) is designed to be a note-taking tool for laptop computers. Notes written in PENS can be published easily in a shared workspace like an Internet WWW page.
- *Hypermail*: Hypermail is a program developed at Enterprise Integration Technologies, Inc. that automatically converts e-mail messages into a cross-referenced archive of HTML documents. In addition, any URLs in the e-mail are also converted to hyperlinks. Hypermail creates four index files of the archive that sort the messages by date received, author, subject and thread.
- *Timbuktu Pro*: Timbuktu is a screen sharing and file transfer application for TCP/IP networks. The screen sharing feature allows remote users to observe or control the operation of a remote machine. The file transfer procedure allows transparent movement of files between machines.
- *Miscellaneous Commercial Applications*: In addition to the computer applications mentioned above, other more common software tools such as AutoCAD, Mathcad, FrameMaker, and Microsoft Project, were used throughout the design process.

Metrics

We have established the following preliminary metrics for measuring the amount of information and the use of tools and media:

- *Metrics for information exchange*: Each discussion of a topic is considered one unit of information exchange. For example: an e-mail message that discusses manufacturing counts as one manufacturing information unit; an e-mail that discusses two issues (in some depth - not just a passing reference) is counted as two units. The same is true for meetings, PENS notes, phone discussions, faxes, and so on. This metric does not take into account the importance and the true amount of information being exchanged. It does not distinguish between a face-to-face meeting and e-mail. While this is a rough metric, we believe it can be useful in our analysis to give us preliminary results.
- *Metrics for the use of tools and media*: Each individual use of one of the tools is considered one unit of use. Each use of a tool to convey one type of information is counted as one unit; if two types of information are covered in one use, it is counted as two units.

Our information units are coarse and non-uniform and include e-mail, meetings, and reports. We have not looked at how much manufacturing information is in, for example, a particular e-mail message. We have counted it as a manufacturing information unit if it is discussed at all, no matter in what depth.

Measures

This section presents some quantitative results obtained from analyzing the cooling system design project. We know that some of the information has not been recorded – especially communications outside the group with vendors and manufacturing service providers. We have not included exchanges (mostly e-mail) that did not contain information directly related to the progress of the project.

Composition of Information

To measure the composition of information, we count the different types of information in the design discourse. Figure 1 shows these quantities for the cooling system design project. Organizational information has the highest number of units exchanged and manufacturing concerns are second. A total of 578 information units were exchanged in the duration of 16 weeks with an average of 36 a week.

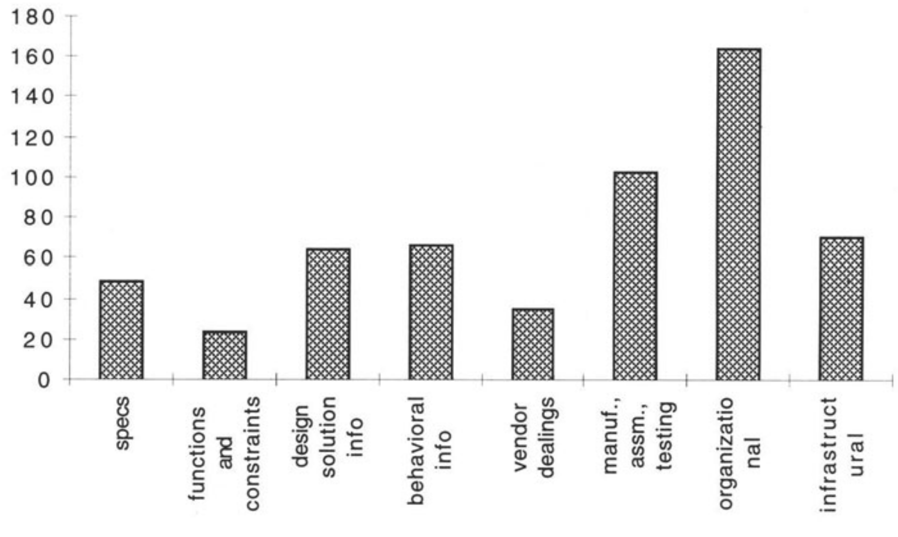

Figure 1: Composition of Information.

Information vs. Time

Information vs. time measures the flux in the domain of design discourse during the design process. Figure 2 shows that manufacturing concerns were discussed throughout the project as were the specifications. The specifications were talked about, refined and negotiated until the end of the project. This concurs with the observation presented by Tomiyama (1994) where he argues that General Design Theory (Yoshikawa, 1981) is incorrect in assuming that all specifications are given *a priori*. Another interesting observation was the low volume of information exchange about functions and constraints. They were rarely discussed explicitly. Our explanation is that this information remained implicit in the minds of designers with no need to discuss it. One consequence of the lack of information exchange about constraints was the relatively late revelation that the current SHARP motor housing had a different configuration than the FMC motor housing.

Information vs. Media

Figure 3 shows the relationship between the type of information and the media used to model and communicate it. Some interesting correlations can be seen between type of information and the tool usage. The limited role of existing CAD systems is apparent too. The use of design tools has been low and has been limited to design drawings and analysis of nearly complete designs. Due to the lack of fineness in metrics used in this quantitative study, the significance of project reports and specific design tools is underestimated to some extent.

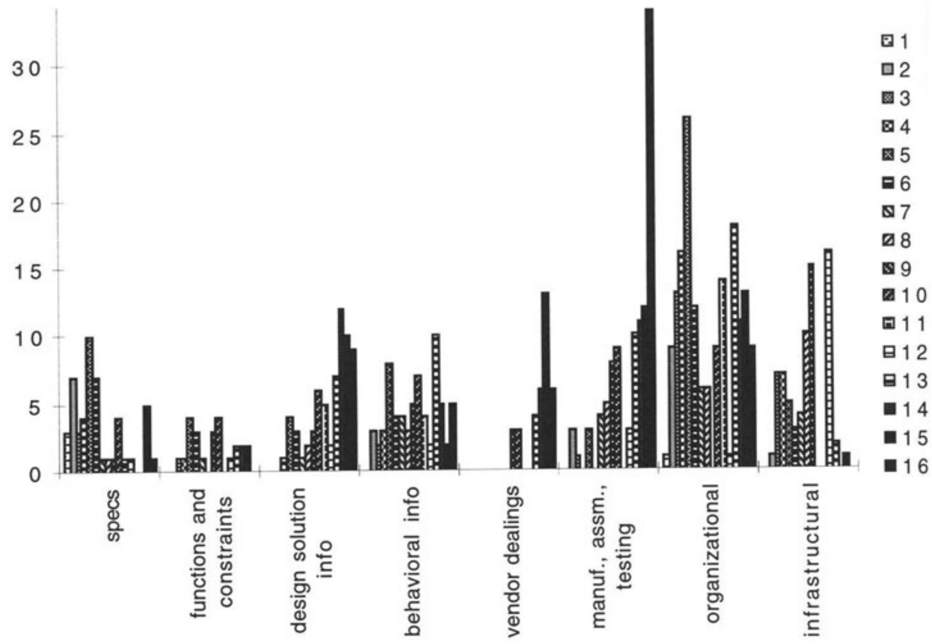

Figure 2: Information *vs.* Time (in weeks, shown from 1 to 16)

Media vs. Time

Figure 4 shows the role of media and tools over time. One interesting observation is the increase in the use of specific design tools and the increase in the use of faxes as the design progressed. This behavior can be explained in terms of development of shared understanding of the information between participants over the course of the project. With time, design concepts became better defined and participants understood the graphical symbols and drawings transferred through AutoCAD files or faxes more easily.

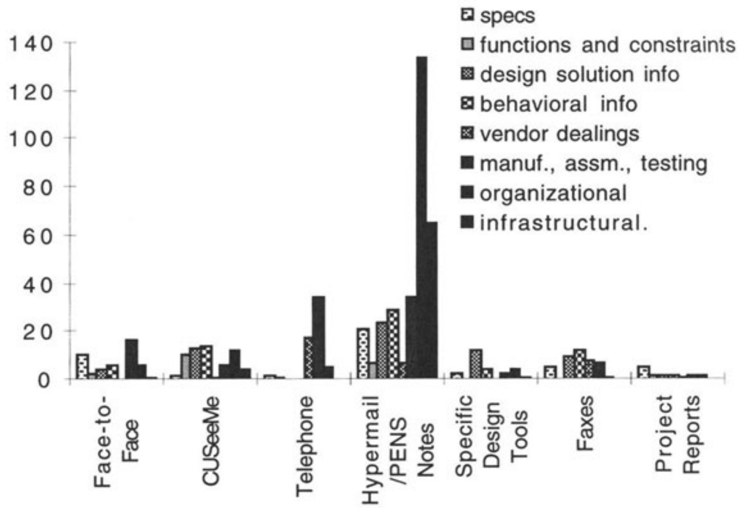

Figure 3: Information *vs.* Media

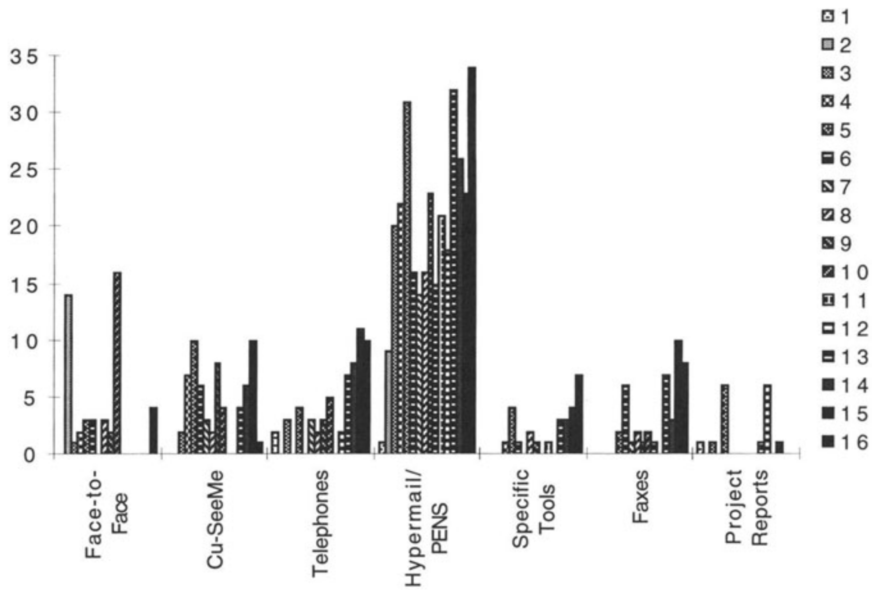

Figure 4: Medium *vs.* Time (in weeks, shown from 1 through 16)

3.3 Measures of Role of Knowledge

In the previous section, we discussed quantitative measures of information. We will not involve ourselves in a philosophical debate over the distinction between knowledge and information in this paper – such a distinction is not essential in this study. For the purposes of this study, when information is assimilated and applied to make a design decision, it becomes knowledge. Our approach to quantifying the role of knowledge in the design is pragmatic. We will first categorize the knowledge and develop some metrics to measure its influence on design.

Categorization of Knowledge

We use the following categorization to cover the range of knowledge that influenced the current design process.

- *Personal knowledge*: Prior knowledge and experience of a designer. This includes one's past experience, creativity, exposure to similar design problems, synthetic abilities, *etc.*
- *Previous design knowledge*: Knowledge about existing similar designs, *e.g.* the previous motor designs. This knowledge facilitates adaptation of existing designs to satisfy current design specifications.
- *Client Information*: Knowledge obtained from the client. This includes client's preferences, bias, and *etc.*
- *Analysis results*: Results of the application of physical principles to predict the behavior of design propositions and evaluate them with respect to the required functions.
- *Manufacturing knowledge*: Knowledge about how the design is going to be made – manufacturing processes, material properties, *etc.*
- *Assembly knowledge*: Knowledge about how the artifact is going to assembled.
- *Vendor knowledge*: Knowledge about availability of design components that can be bought off-the-shelf.
- *Miscellaneous knowledge*: budget, time, and *etc.*

Metrics for the Role of Knowledge

The following two basic assumptions underlie our metric for the role of knowledge: design is a discrete process that involves many design steps and the influence of a particular type of knowledge on a design step can be measured. With these assumptions, we count the number of times a particular type of knowledge causes a design step to be taken. Each time a design step is made, the step is attributed to the influence of one type of knowledge. Since all design steps are not of equal importance in a design process, we define three categories of steps: topological, configurational, and detailed. Topological design steps deal with high-level attributes of the design – most steps during the conceptual design fall in this category. Configurational design steps deal with embodying the design concepts into a physical artifact. Detailed design steps deal with fixing dimensions, tolerances, *etc.* While the terms topological and configurational are often used in the context of form, here these terms also refer to non-geometric information such as material. For example, topological information about material might be the recognition that a part needed to be non-electrically conductive and able to withstand high temperatures; configurational information would refine the choices to fiberglass or plastics; and detailed information would specify an engineered thermoplastic like Polyetherimide.

Measures

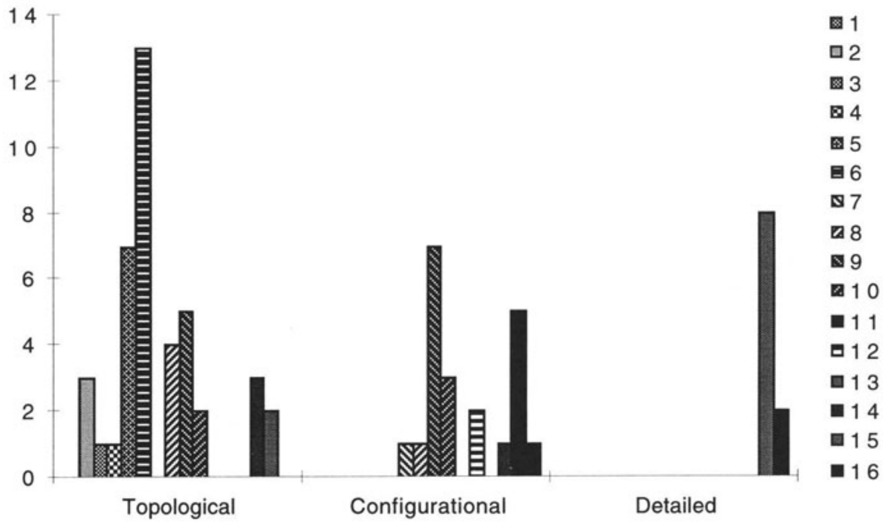

Figure 5: Design Steps *vs.* Time (in weeks, shown from 1 through 16)

Figure 5 shows the number of design steps with respect to time; Figure 6 shows the role of different types of knowledge with respect to time. As one would expect, most topological steps are at the beginning of the design process, although some topological changes take place toward the end of the project due to additional knowledge about manufacturing processes or because part suppliers could not supply what designers needed. As Figure 6 shows, the personal knowledge of participants played a major role at the beginning of the project, with its gradual reduction over time. Toward the end of the project, manufacturing concerns, analysis results and vendor information dominated. The role of knowledge is measured on the basis of explicit discussions about design decisions. Many design alternatives may have been eliminated because they were obviously not manufacturable, but these eliminations are not attributed to manufacturing knowledge unless explicitly mentioned.

Figure 7 shows the types of knowledge used in different design steps. Note that analytical results played a small role in topological and configuration design, and none in the detailed design. This lack of influence occurred because analysis was a parallel activity and could not provide simulation results in time. The analysis group had to work on developing models for analysis. The next time a similar design is undertaken, analysis results will certainly have more impact on the design. We will have better models of the design and greater need to optimize the design. Personal knowledge has the greatest role in topological design stages, followed by the previous design knowledge about such design problems and solutions. Note the substantial role of manufacturing knowledge in the topological design.

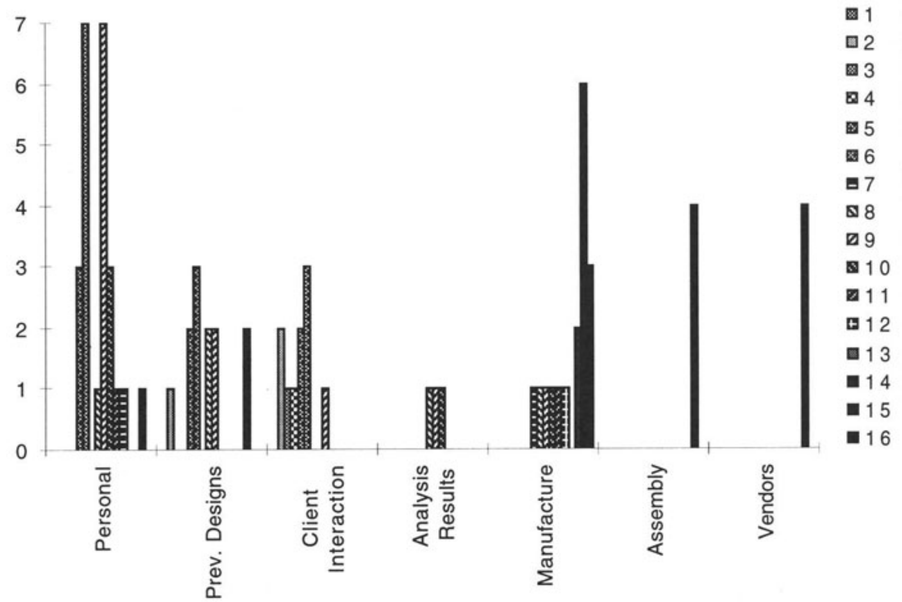

Figure 6: Knowledge *vs.* Time (in weeks, shown from 1 through 16)

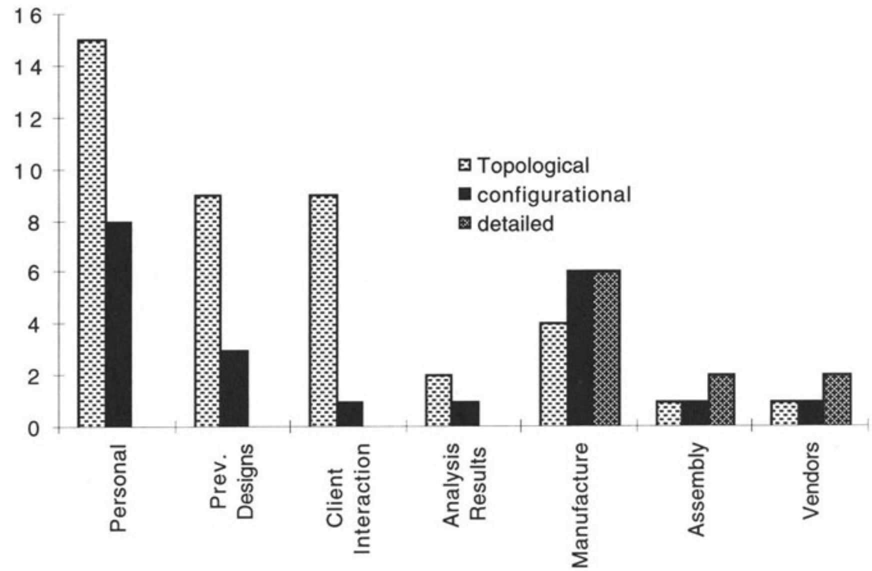

Figure 7: Knowledge *vs.* Design Steps

4 KNOWLEDGE INTENSIVE CAD

The purpose of the paper has been to demonstrate the knowledge richness of design discourse, to identify which types of information and knowledge played a significant role in the process, and to understand how they were communicated. Both aspects – what and how it was communicated – are important for the discussion of knowledge building. we have not presented the "what" aspect in detail in this paper; we have only classified the knowledge into general categories. However, despite the coarseness of the measures, we believe they reflect general patterns in the design process. We have been able to relate most problems in the design process to some pattern, or lack of expected pattern, in the measures.

4.1 The Role of Knowledge-Intensive CAD

The essential characteristics of the design problem under study are that: the designed artifact was non-routine, without well-defined, pre-existing models of knowledge related to its physical behavior or manufacture; it involved multiple participants; and it spanned from conception of need to concrete realization of the artifact. For the purpose of elaborating the concept of knowledge-intensive CAD, we will discuss the question: what could have been the role of knowledge-intensive CAD in the design project under study?

As long as humans are the primary agents who interpret and use knowledge, the role of knowledge-intensive CAD seems to be limited to the efficient knowledge retrieval based on the design context and to the transfer of this knowledge to designers at the correct time. This leaves open the issue of how to develop the required knowledge in the first place. However, if we wish to support designers in interpreting, reasoning about, and using knowledge, additional issues arise. Development of models (structured and computational) of knowledge becomes necessary along with development of knowledge itself. Models of knowledge reveal the structure of the knowledge and aid in interpreting and applying it to the problem at hand. Keeping this distinction in mind, let us enumerate and briefly comment on the various types of knowledge as categorized in Section 3.3.

Personal knowledge, as indicated in Figures 6 and 7, played a major role during the initial stages of the project primarily in developing conceptual solutions for given specifications on the cooling system. Characterization of this knowledge is most difficult, and we will not attempt to do so here. Several efforts, especially those using knowledge-based systems and expert system paradigms, have attempted to incorporate this knowledge in design systems with a limited degree of success in narrow domains. More recently, efforts are underway to generate designs from behaviors and physical principles; however, the question remains: how can we supplement human knowledge?

Previous design knowledge played the next most important role in generating conceptual design solutions. Most of this knowledge is derived from the history of the project over the previous two years and from the client, FMC. The means of communication involved face-to-face meetings and inspection of engineering drawings of the previous and existing designs. Relatively recent efforts in case-based reasoning and other methods address the issue of design reuse. Some research efforts have attempted to generate alternate designs, while others have attempted simply to retrieve and present relevant cases to the designer to interpret and reuse.

Thermal analysis played a small role in the conceptual stage of design. Analysis models at this stage were approximate, but served the purpose of evaluating early designs. Detailed models were not available and hence were not used in detailed stages of the design. The relevant questions here are: do we have adequate analysis and behavioral models for the physical phenomenon? can we automatically generate these behavioral models (*e.g.*, thermal and fluid-flow models in the project) from the given design description? how do we know what models are important? what models are sufficient? what factors dominate?

Manufacturing and assembly knowledge, in combination, played an important role throughout the design process. The acquisition of knowledge occurred from many sources including design handbooks, manufacturing text books, manufacturing personnel and personal communications. Currently, the design-for-manufacture research area is quite active. The most important issue is the development of models of manufacturing processes for use by designers. One approach is simply to make this knowledge accessible quickly and at the correct time. The knowledge must be indexed, and the retrieval mechanisms must be intelligent. A typical question in the design project was: "Tell me about machining fiberglass tubes with a thickness 0.08 inches." A more ambitious approach is to automate the manufacturability analysis of designs. This approach involves development of computable models of manufacturing processes.

Knowledge about what was commercially available altered the design outcome significantly. This knowledge is acquired by catalog search, from inquiries with more experienced designers, and from vendors themselves. Communication were informal and mainly via personal meetings and phone. As with manufacturing knowledge, both computable and non-computable models are possible. Research efforts such as PartNet (1995) are currently addressing this issue by providing on-line catalogs with capabilities for search and selection. Ideally search capabilities based on functional description of the solution sought also are to be provided.

4.2 Knowledge in Design Environments

Let us briefly comment on the existence and growth of this knowledge in design environments. In the current context, the term design environment includes all tools that support design activities including specific design activities (such as drafting or stress analysis), documentation, team collaboration, and information provision and retrieval. More importantly, it includes codified knowledge (*e.g.*, documents describing previous similar designs) and the available computational techniques that operate on this knowledge. Usually, design environments cannot support a design process completely, in the sense that they do not have the complete knowledge required for the design process. Designers must seek out information and knowledge relevant to the context. The vast amount of effort by designers in seeking appropriate information, elaborate discussions and negotiations, experiments and trial and error, are few indicators to corroborate the fact that much of the knowledge gets built and shared during the design process. Such contextual knowledge, if captured, can enhance the overall design environment. Hence, a design environment should be open and be easy to update with new knowledge. By building knowledge related to a particular product or a set of products, the corresponding design process is made more routine, formal, and computable.

A knowledge-building design environment is the antithesis of an integrated closed, self-contained design system that supports a specific design process for a specific product. Such systems typically assume the existence and availability of the complete body of knowledge required for supporting the process. This assumption makes these systems fragile and applicable only to specific design problems in specific contexts. These limitations arise partially because we do not yet have methods for designing from general principles, even for specific domains. In the absence of such understanding, in most design problems, especially in domains where technologies change often, the process of design involves creating new vocabulary, new techniques, and new models mixed with the existing vocabulary, techniques, and models. This ingenious mixing of elements of available knowledge and newly generated knowledge applicable to the current context is a significant part of the design process.

4.3 Current Research

Our current research is motivated by a simple but important observation that design involves not only knowledge use, but knowledge building as well. In our work under development (Reddy, 1996), we develop a notion of *artifact theory* and argue that designing an artifact is essentially equivalent to composing a theory about that artifact by bringing in all the relevant knowledge and systematizing it. The uses an artifact theory developed through the design process are many: we can reuse and adapt the theory in other (similar) situations, inquire about the artifact, make predictions about the behavior of the artifact due to any modifications, and so on. Such theory building may involve both development of new elements of the theory and reuse and adaptation of elements of the existing theories. An important implication of this view of design is that design environments should support both theory building and theory use in a cohesive manner.

Our current research focuses on the following topics: establishing design as artifact theory building and reuse; elaboration of artifact theory; understanding development of artifact theory and its capture; supporting capture and reuse of artifact theories, and demonstrating uses of the view of design as theory building; and proposing artifact theory as a vehicle to understanding design. In this overall context, one of our hypotheses is that theory is expressed and made explicit in the discourse between participants of the design (both human designers and computer tools). The study presented in this paper is a preliminary verification of this hypothesis. More detailed investigations are underway.

5 CONCLUSIONS

In this paper, we have argued that support for knowledge building in design environments is essential. We have presented an analysis of the discourse in a case study to show that design discourse includes a variety of knowledge and that systematic capture of this discourse can be a means to knowledge building. The analysis measures developed in this study, although rough, reflect patterns in the design process and indicate the design support required. Our current research focuses on the discourse concerned with artifact information and involves identifying elements of knowledge and developing conceptual structures that capture artifact information and support knowledge building.

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