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computational tools that should be built to support it.

# 7 Summary and Future Work

We have presented quantitative and qualitative results from an empirical study of design information reuse during redesign. A framework has been developed which characterizes the different kind and types of information that are needed during reuse and should be captured. A notion of critical information has been explored, as infromation which leads to leaps in understanding of the design problem and affects the flow of the downstream design process in a big way.

We have used the framework presented in this paper to design a vocabulary for indexing formal and informal design information. The quantitative results are guiding how we decide what infromation to keep and what to filter out in the Engineering Design Notebook. It is also providing a mean for prioritizing design information and using this priority in many ways including during retrieval.

In the future we wish to extend the approach of experimental methods to study use of existing and new design tools and develop metrics for instrumenting the design process. With a method to measure critical parameters, it would then be possible to monitor these measure in the dynamic nature of this process and this would open doors to research in the realm of developing accurate models of the design process.

# 6 Discussion

There are significant differences in the results of this study and the study reported in [6]. We have shared some reasons for the difference above. Some other reasons and factors which can influence the outcome can be attributed to the following:

- The size of the design problem will influence the range of the question one would encounter. In [6] the first generation design problem was solved in an experimental setting over a period of 16 hours and the documentation available to the *subjects* were the machine drawings with specifications. However, in our case the first generation design was done in the real world and the documentation was quite extensive. The bigger scale of the design problem exposed us to new kinds of questions which may not have occurred in a simpler problem.

- The questioning behavior is not random. New questions are asked by a designer after reflecting on information he/she received in answer to previous questions. So the type of questions asked can depend heavily on how and in what form the information is made available to the designer. For instance, if a designer was given a machine drawing it would be very likely for him to ask questions about location and connections, however if the same information was given to him in a descriptive form, the line of questioning would be quite different.

- Because of the poor understanding of the design process, its objective evaluation is very difficult.

Our attempt is not to generalize the results we obtained but to show experimentation as a useful method for studying the design process and developing requirements for

uninteresting questions belonged to *miscellaneous* descriptor while the most critical questions belonged to the *relation* descriptor.

Table 6: Combination of descriptor and criticality

Table 7: Combination of level of detail and criticality

Table 7 suggests that most of the uninteresting questions belonged to the conceptual stage while all the critical question belonged to the detail stage. The results of table 6 and table 7 may be because of the peculiarity of the experimental procedure. Since the designers have a limited time in the experiment, they do not think of making any conceptual changes in the design and quickly resolve to finding a solution by manipulating certain key parameters. This way they commit themselve to dealing with the detailed stage alone. This phenomena was observed in both the experiments.

is approached by first determining the differences in the new and old requirements, this approach was also observed in both the experiments.

Table 5: Combination of Descriptor and subject class

Number of question which were judged very critical (criticality = 2) was low but significant. On the other hand the number of uninteresting questions (criticality = 0) was quite high suggesting an exploratory nature of the designers. Table 4 indicates that more than half the questions were addressed to the details of the design, but at the same time more than a quarter of the questions are addressed at the conceptual stages of the design. This signifies the need for capturing information from conceptual phases along with the information from the detail stages.

Tables 5, 6 and 7 contain an ordered listing of combination of two of the classification categories. Only some of the interesting combinations are shown. Table 5 suggests that most *relation, performance, construction* and *miscellaneous* questions were on *features*. Combining criticality with the descriptor suggests that most of the

question with *miscellaneous* descriptor. This suggests there strong interest in digging out information relevant at the level of the design process (such as strategies, opinion on concepts, methods of evaluation) rather than just at the level of the device alone. The classification of [6] does not take into account these kinds of question since their classification seems to deal at the level of the device only. Besides the *miscellaneous* questions the designers asked about equal number of questions in *performance*, *relation* and *operation* descriptors. Unlike [6] we did not find as many *location* questions. A possible explanation could be the different understanding of the *location*.

Table 3: Criticality Classification Results

Table 4: Level of Detail Classification Results

Within the subject class about one third questions were asked about *features* and one fifth about components. There were significant (13%) questions on the requirements of the design, which is expected in a redesign situation since in most cases the problem

preferred to look through documentation more often than asking questions. Another possibility is that *subject2* being a more experienced designer asked fewer but pertinent questions and therefore took about 2 hours less than *subject1* in coming to a solution. The results of classification of questions are in table 1, 2, 3 and 4.

Table 1: Descriptor Classification Results

Table 2: Subject Class Classification Results

From table 1 it can be inferred that both the *subjects* asked about one fifth of their

3. *Critical:* criticality = 2, the answer resulted in a big leap in the understanding and progress in the design.

### 4.4 Level of Detail

If we were to classify the information about the previous design on its level of detail, then the level of detail of the answer to the question is the level of detail of the question. The evolution of a design is very commonly perceived as passing through the three stages, namely: *conceptual, configurational* and *detail.* These stages differ in the level of detail that is available about the design. A classification on the level of detail will provide a measure of how many questions are addressed to each of the level of detail, signifying how much attention should be paid in recording information at that level of detail.

We also classified the question based on their type as to whether they were confirmation, explanation, conjectures or not and on what would be the most appropriate medium (text-graphic, equations, simulation, video, audio) in which to answer the question. The results from these are guiding the development of a retrieval system on top of the Engineering Design Notebook.

## 5 Results and Their Explanation

We extracted 160 question from the first experiment and 80 from the second. One possible reason for this large difference can be that *subject1* was familiar with the *expert* and felt comfortable asking question whereas *subject2* who was not that familiar

Requirement occurs in the descriptors as well as the subject class since a requirement can be a subject of a question as well a question can be seeking information regarding the requirement of some subject.

## 4.3 Criticality of a Question

The criticality of a question is considered here to get a measure of what impact the asking of the question (and getting an answer to it) had on the overall goal of accomplishing a design. In other words this measure reflect how severely the downstream design process was affected as a result of the question. It also suggest that if the question had not been asked would the design process been any different or not. This measure is essential since designers ask many questions and only few of those questions are critical or lead to leaps in their understanding of the design problem. Being able to identify these questions would give us a methods for prioritizing information about the design. In assessing these measure we were careful to consider effects immediate as well as anywhere downstreams. The assessment of this measure was quite difficult and we often had situations hard to resolve. However, as an initial step we have defined a very low granularity scale, a scale of zero to two, which allows only the most critical (or not-critical) questions to be easily identified and the rest falling in a middle category. We have tried to be rigorous and utilized help from the experiment *subjects* in resolving conflicts.

1. *Uninteresting:* criticality = 0, the answer had no affect whatsoever on downstream process.

2. *middle:* criticality = 1, the answer had some effect.

eg: Is the shape of the volume of the damper a cylinder?

2. *Component:* the question subject refers to a component, or a collection of them, but with interest at the component level.

   eg: Does this end of the arm go +3 top to −3 bottom?

3. *Connection:* the question subject refers to the interface between two or more components.

   eg: Is the disk attached to the hub?

4. *Feature:* the question subject refers to the detail of a component or assembly or a connection such as dimension, state etc.

   eg: How does the stroke length affect the torque?

5. *Requirement:* the question subject refers to any of the requirements of the design.

   eg: How heavy was the last design? (weight was one of the requirements)

6. *Design Concept:* the question subject refers to any of the design concepts of the previous design or concepts he/she has generated.

   eg: What were the drawbacks of the other design concepts the first designer considered?

7. *Other:* the question subject refers to something that does not fit in any of the above classes, such cases were rare but enough to be classified separately.

   eg: What are these four lines in the graph of the solenoid for?

6. *Rationale:* information regarding the purpose or the function of the subject or reasons for the subject being the way it is.

   eg: Why did they use Kevlar?

7. *Relation:* information regarding any relation between the subjects, their comparison, sensitivity to each other.

   eg: What is the effect of the temperature on the solenoid?

8. *Requirement:* information regarding constraints or the specifications of the subject.

   eg: What was the stroke length limit in the previous design?

9. *Miscellaneous:* information which does not belong to any of the above type, for instance, information about the vendors, references, about strategies, opinion on particular choices and others. In most cases these questions were at a process level rather than the level of the device or part thereof. For lack of a better term we are calling this category miscellaneous.

   eg: What are the characteristics of the suspension system?

   eg: What do you mean by ON-state?

## 4.2 Question Subject Class

The subject of a question is the subject of the sentence or the clause representing the question. The subject can belong to one of the following classes:

1. *Assembly:* the question subject refers to the whole assembly or a subassembly or a collection of component with interest at a level above individual component.

also helped us maintain objectivity in classification.

## 4.1 Question Descriptor

The descriptor of a question refers to the character or nature of the information that is sought by the question. The word "subject" below refers to the subject of the question.

1. *Alternative:* information regarding the choices or the decision about the subject.

   eg: What are the other ways of changing linear motion into rotary motion?

2. *Construction:* information regarding the topological arrangement of subject(s) as well as details of how they are put together and their details (shape, dimensions, weight, volume, manufacturing process etc.)

   eg: What does the old damper design look like?

3. *Location:* information regarding the physical position of the subject in the device.

   eg: Where do you want maximum resistive force in the full ON state?

4. *Operation:* information regarding the manner of functioning of the subject.

   eg: How is the amount of the friction changed?

5. *Performance:* information regarding the evaluation, analysis, test results of the subject.

   eg: What are the limits on force and temperature of this solenoid?

# 4 The Question Framework

The most difficult and debated part in this study was the building of the framework which would remain consistent across different design domains and was above the peculiarities of the specific design problem we had chosen for the experiment. After much thought and debate, we consider the following to be the important categories in classifying questions:

| Descriptor | Subject Class | Criticality |
|---|---|---|
| alternative | assembly | 0 |
| construction | component | 1 |
| location | connection | 2 |
| operation | feature | |
| performance | requirement | Level of Detail |
| rationale | design-concept | conceptual |
| relation | other | configurational |
| requirement | | detail |
| miscellaneous | | |

In a general way each question can be interpreted as: the *subject* is requesting a **LEVEL OF DETAIL** information regarding the **TOPIC** of the **QUESTION-SUBJECT** which belongs to **SUBJECT-CLASS**.

The **QUESTION-SUBJECT** refers to the domain dependent subjects of the question. Along with the reformulation of questions, the above manner of interpretation

# 3 Analysis of Verbal Data

Figure 1 shows the stages involved in reducing the recorded data on tapes to a form which can be studied.

Figure 1: Stages in the analysis of verbal data

For the purpose of this study a question is any sentence or clause utterance from the *subject* which expresses a need for information or confirmation. After identifying the question the corresponding sentence or clause utterance was extracted from the transcript. This extract was reformulated into a complete question by filling in missing information from context.

The classification of question was based on the reformulated questions. Making the questions a little formal helped us do away with a lot of subjectivity and judgement during classification.

done by a three member design team for Ford Motor corporation over a period of about seven months [1]. In this project they carried out the design from concepts to laboratory testing of a prototype. As part of the seven month endeavor they produced three documents equally spaced over that period. Each document summarized the status of design up until when it was written. Thus, all three together captured the evolution of the first generation design from the early ideas to the final machine drawings and results of laboratory tests. We also had copies of all the personal design notebooks of the three designers. We provided the *subjects* in the experiments, access to all the documentation and the notebooks. One member of the original design team, to be referred to as the *expert*, was also available to answer questions and serve as an index to information in the documentation which totaled to more than a thousand pages. The method of the *subject* using the *expert* as an index provided a natural way of making the questions explicit without being obtrusive to the *subject's* working.

The *subjects* were requested to complete their work in about six hours over two sessions with a break in between. The *subjects* were also asked to summarize the status of their work before and after the break to capture any questions that may have occurred to them during the break. We conducted two experiments with one subject in each of them. *Subject1* was a graduate student with more than 2 years of design experience and *subject2*, who was from an industry, had more than 10 years of design experience. The subjects were audio and video recorded during the experiment. The first experiment lasted about five and a half hours and the second one three and a half hours.

used in conducting the experiments and collecting the data are quite similar. The differences lie in the choice of the design problem, the scale of the first generation design, the level of documentation available to the designer, the analysis procedure and the results. We will explain and highlight other differences as we discuss the details in the sections below.

# 2 The Redesign Experiment

Since we were interested in understanding and formalizing the information needs of designers during redesign of an artifact, we designed the experiments to maximize the ability to capture data reflecting this need. It is very natural for us to express our information needs in the form of questions. So, if we were to capture all the questions that the designers have during redesign, we would have a tangible data reflecting the information needs of the designer. We performed controlled experiments using the verbal protocol method, which has been used in the past for studying design by having subjects make their thinking process explicit [14].

The design problem chosen was the redesign of a continuously variable car damper[3] to meet a new set of requirement specifications. The new requirements were defined such that the *subjects* would be able to come to a solution within the duration of about six hours, while still requiring them to develop a good understanding of the design before coming up with a solution. Such a tradeoff was essential to conduct an experiment in a laboratory while still ensuring ample opportunities to captures information needs. The first generation design was a real world industrial design

[3]Popularly known as the shock absorber.

Related work in this field has focused on structured methods of obtaining information from designers and incorporating this information in a knowledge base [3, 5, 4, 11]. These approaches have focused on specific kinds of information such as design rationale and decisions and either require designers to have special skills in using a knowledge-based tool or need knowledge engineers who extract knowledge from designers and transfer it to the knowledge bases.

## 1.1 Objectives of the Study

We undertook this study with a couple objectives in mind, one to support the method of controlled experiments as a method of studying design and defining requirements for tools which should be built to support this process, and second to develop a framework for the information needs of designers which would guide the building of a tool to support its reuse.

Experiments as a method to study the design process is gaining momentum. It is an approach which allows us to look at the design process very closely from any perspective of interest. However, experiments involving human subjects are a challenge to control and monitor, since results can be easily influenced by the human subject, the choice of the design problem and person interpreting the data. We need to develop method and techniques to overcome these barriers so that results can be extracted independent of these influences. Some of the past work in experimentation has attempted at developing models of the design process [13], understanding function and form reasoning of expert and novice designers [2].

A study similar to the one in this paper has been published in [6]. The methods

and others. A perspective that we wish to share in this paper is the perspective on design information, and specifically its reuse. It is appropriate at this stage to ask, what is design information? In this study design information refers to all data that is generated, used, referred to, consulted with during the design process from the early conceptual stage to the final detail design stage.

It has been realized for quite some time now by the community of industry designers as well as the community of design researchers that reuse of design information is much more cost and time effective than regenerating that information. It has also been understood that capabilities of current CAD tools in recording information is far less than what is needed to realize the benefits of information reuse. Current CAD tools typically only capture the final design details in machine drawings and a few other related details such as specifications, analysis results etc.

The complexity of the design process presents many challenges in building tools which would support the design process from early ideation stages to the detail design stages. Among other things, the tools should be able to record and structure the information being generated and used, in a formal manner so that it can be reused at a later time. At the Center for Design Research we work with a prototype Engineering Design Notebook called vmacs$^{TM}$[2] which is a specialized text-graphics editor capable of supporting early conceptual design stages and providing access to CAD tools used in the detail design stages [8, 12]. The notebook provides one medium within which designer can perform all design related activities and thus this medium is able to record all activities of a designer during the complete lifecycle of a design project. The data captured this way has been used for many different applications [7, 10, 9].

[2] vmacs is a trademark of Performance graphics company.

# An Experimental Study of Design Information Reuse

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## Abstract

We are reporting results and experiences from an experimental study conducted to study the nature of design information reuse during redesign. Starting with a detailed study of the questioning behavior of two designers, we have developed a framework for understanding the character and the basic constitution of information that should be recorded during design for the reuse process to be useful and productive. This study lays the ground work for future work in recording, characterizing and indexing design information as it is generated during the design process.

## 1 Introduction

Design in any engineering domain is a very complex activity. We as researchers look at this activity from various perspectives such as technical, methodological, social

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