

# Notes on Empirical Studies of Engineering Tasks and Environments

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## Introduction

Study of design and norms for designing dates back 2000 years when Vitruvius first wrote his book on architectural design and prescribed what a designer *ought* to know and how he/she *ought* to behave. In recent times, the perceived need to organize and systematize design started with the first conference on design in 1962.

Subsequently, there have been numerous conferences and articles on various aspects of design. There are two distinct schools of design: a) prescriptive and b) descriptive - former being most prevalent. After almost two decades of approaching design mostly from a prescriptive point of view, in 1979, Bessant (1979), called for more emphasis for description, maintaining that,

...there has been a move away from prescribing what people should do and towards what they actually do do. From analysis of this descriptive data, it becomes possible to derive improving performance ... relevant to the observed situation. [p.77]

Some of the main concerns raised in our 1991 workshop on “Information Access and Capture,” can be expressed in the following questions:

“What do we know about what engineers do?”

“What are their needs?”

“What information do they use?”

“How do they go about organizing and retrieving information?”

“How do they communicate?”

“How do we go about answering these questions?”

The move towards observational studies proposed by Bessant (1979), has yet to take hold in the engineering disciplines in any significant fashion. As Larry Leifer, pointed, in the workshop, NSF has not funded a major empirical study in design. In general, there is an aversion to studying design due to the time consuming nature of the process and a persistent belief that engineering is a purely technical process or there is a clear dichotomy between the technical and social.

Nevertheless, there has been some interest in studying design empirically and in these cases the primary concern is methodology. Methods<sup>1</sup> discussed in the design research literature to date have been derived from behavioral sciences (psychology, sociology, organizational studies) and adapted to the design process. As has been emphasized by several researchers (Bessant, 1979; Tang, 89; Hales, 1988), there does not exist a single method for studying design. In fact, a multiplicity of methods should be used depending on the context both to cross check the data and construct a clearer picture of the process. This position paper agrees with this call for description and understanding in design studies. In what follows, a summary review of dimensions and methods of design studies will be provided. Based on this review, a need for more studies and development of

methodologies<sup>1</sup> to address the lacunae that exists in the current understanding of design is recommended. A proposal for computational or other aids to improve design practice should be based on such studies. The rest of the paper is divided into three sections. Section 2 identifies the dimensions of studies in engineering design and includes the units of knowledge and information that needs to be acquired. Section 3, provides a brief review of methods that have been used in studies of design along with their limitations. The final section deals with conclusions and recommendations calling for further studies as partnership between academia and industry.

## **2. Dimensions of Studies in Engineering Design**

Design of products takes place in variety of settings that vary from an individual designing an artifact to multiple organizations involved in the design of very complex artifacts such as automobiles and aircrafts. Here, the critical dimension identified in the design process is the multiplicity of persons and perspectives and sources of knowledge involved. This leads to a requirement that design studies be conducted at different levels of social granularity and knowledge.

### **2.1 Design Units**

Design takes place in and across<sup>2</sup>:

#### **a. Social Units**

- Actors (artifacts and humans)
- Individuals
- Small Groups
- Large Organizations
- Multiple organizations

#### **Structures**

- Norms
- Roles

#### **Situations**

- Synchronous (face to face)
- Asynchronous (indirect media)

#### **b. Knowledge Units**

- Specialized knowledge/single domain
- Integrated knowledge/multiple domains

Conceiving of design as taking place in and across social and knowledge units facilitates the study of the process and content of design. A knowledge unit is carried by social units of design processes, though more than knowledge unit can be carried by any given social unit. All design activities are situated in social and cultural contexts in which such social

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<sup>1</sup> As ever, the confusion about methods and methodology persists. In this position paper, when we use Methodology we mean a variety of methods suitable only to specific contexts.

<sup>2</sup> We do not intend this to be an exhaustive analysis only indicative of some of the complexity involved.

units as customers, vendors, users, etc., interact. In order to understand design tasks and environments, studies will have to be conducted in an integrated way at *all* of these levels.

## **2.2 Design Units Through Time**

Another important dimension of the study of design is the relative maturity of designs. New designs are those that have only indirect or partially understood precedents while mature designs are those that have a history of well understood direct precedents. The distinction between new and mature designs is important though difficult to operationalize since *both* draw on an accumulation of knowledge derived from the evolution and relative stabilization of required functionalities, failure modes, performance characteristics, design trade-off criteria, etc. In the case of mature designs, cognizance of these attributes in previous versions of the designs is directly applicable to the design of subsequent versions. However, operationalizing the notion of directness of applicability of prior designs is a complex problem requiring the development of new methods. Experience with development of designs, whether new or mature is generally scattered across knowledge sources that may span divisional boundaries of an organization and sometimes multiple organizations. Even for mature designs, changes in one or more knowledge sources and/or markets require that new ideas have to be integrated in the redesign of these designs. In this sense, both new and mature designs involve information and knowledge sharing, so it is critical to develop methods to comprehend the effects of interpersonal, organizational, and work structures to facilitate effective information exchange to prevent breakdowns, bottlenecks, problems, and errors in subsequent versions of the design process.

## **2.3 Dimensions of engineering design relevant to information acquisition**

For the purposes of the workshop, the above dimensions have to be applied to its main focus, “information access and capture in engineering design.” Since the primary purpose of studying design tasks and environments is improving design practice through effective information and knowledge sharing, an important aspect of the study of design practice is understanding the interaction between generation of information, modes of exchange, and media for communication and accumulation of information according to the design dimensions described above. Studies to date point to the richness in a variety of media and modes of accumulation and exchange across all these design dimensions (Clark and Fujimoto, 1991; Hales, 1989; Leifer, 1991; Tang, 1989; Subrahmanian 1991; Ullman, 1989). Knowledge and information media include the use of paper, physical models, and human body. The modes of exchange include the form of text, sketches, drawings, video, film, pictures, gestures, and speech.

## **3. A summary of methods based on existing studies.**

A variety of methods have been used in the studies reported in the literature at various levels of granularity. Most of the studies however are confined to studying individuals due to the strong influence of cognitive science to create computational models of expertise. There has also been a trend towards building computational tools to capture

design knowledge. Most of these computational techniques that capture knowledge have been restricted to cataloging domain knowledge for particular tasks. Table 1 provides a summary of methods that have been used at the different levels of granularity. One important point that needs to be stressed is that no single method will provide complete information either on the process or domain. A number of techniques have to be used in conjunction to create a robust picture of engineering tasks and environment. Concentration on single individuals designing for mostly toy problems is due to the academic nature of many of these studies. Design very seldom takes place in actual practice only at individual levels. The relative sparseness of studies at higher levels of granularity reflects the need for a greater effort toward gathering data and developing methodologies to analyse data using methods from the social sciences. As was pointed out in the workshop, engineering design researchers need not become anthropologists, sociologists, or organizational theorists but need to be both aware of work within these disciplines and also create interdisciplinary teams to study design from each of the levels of granularity that have been identified. The process of studying design should not be construed as a one time set of studies that will answer the problems of effective design. The stance of the design study undertaken will vary with time and context due to needs and changes in design practice by the introduction of new computational tools, work practice, changing social environments etc. Further, there also exists a gap in the efforts towards building comprehensive domain knowledge in a given domain of expertise wither disciplinary or product based (necessarily multidisciplinary) that can addressed using some of the methods outlines in Table 1 under domain units. A number of the proposals that were put forth either during discussions at the workshop or in the course of the presentations by the participants in the workshop that address some of the needs and lacuna in design studies described above. These will now be described.

#### **4. Proposed models for Empirical Studies**

Several studies, some of them described during the course of the workshop in different presentations and talks that fall in one of the above dimensions are proposed as:

**In-situ studies:** Studies of industrial practice by the use of participant observer, direct observation, and other techniques in industrial settings was suggested. Studies such as those of Hales(1988), Stomph-Blessing (1991) are examples of in-situ studies. New studies with specific focus on the types of information to be acquired should be initiated and in many cases appropriate methodologies developed, especially in co-ordination with the development of new tools for design practice.

Tools such as n-dim, Object Lens that were presented in the workshop can potentially aid not only designers but also aid in collection of data for design studies(Malone, 1991, Subrahmanian, 1991).

**University based studies:** Leifer suggested that studies of small groups of students designing artifacts to address real life industrial problems can serve as a laboratory for studying design as well as provide invaluable training to students on real design problems. Appropriate arrangements with industry to remove proprietary information will

have to be developed. Further, this laboratory will result in microcosms for testing the use of new tools in design practice (albeit simulated).

**Xerox Webster-information-use studies:** Xerox Webster is currently conducting studies on information use by including an information specialist in a design group to study its needs and use of information (Majcher, 1991 this workshop). Here, the information analyst serves both as conduit for searching current repositories as well as describing the environment for design based on information needs and uses. Such studies are useful in understanding information re-use, dissemination etc.

**Trade-studies:** Supporting and understanding trade studies like those at Boeing should also be expanded. The work by Boose et al. (1991) serves as an example where a number of methods and tools including rationale capture and personal construct based knowledge acquisition tools are used.

**Domain studies:** Use of knowledge acquisition tools that employ a variety of methods such as personal construct theory, interview and domain analysis based ontology creation for particular domains (materials-Sargent, 1991, general tool for ontology creation - Monarch,1989, Skuce, 1989, thesaurus construction - Monarch, 1991) will also have to be undertaken to understand and codify the domain terminology as well as supporting intelligent information retrieval.

**Organizational studies:** There are very few organizational studies on information flow, accumulation and update from the the view of product information. The only major study known is by Clark and Fujimoto (1990) that approaches product development from the perspective of integration of problem solving at different levels and across phases of design. This study is also a cross-national study in the automobile industry. More such studies in different industrial contexts are necessary to understand variations across industries and across national boundaries.

In conclusion, what we find is that the richness of engineering design from a social and technical perspective demand that we develop integrated methodologies that are derived from a number of social science and technical disciplines. This position paper is a start in identifying the range of studies and the need for sharing data and information that can be analysed from a variety of perspectives to provide as comprehensive a picture of engineering design as possible. From this more comprehensive picture, we will generate better design aids. Furthermore, the process of introducing design aids in turn will result in changes in work practice that will again have to be studied for a continuing understanding of interaction between the social and knowledge units.

#### Acknowledgments

I would like to thank my colleagues Yoram Reich, Ira Monarch and Suresh Konda for their comments on earlier drafts.

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**Table 1: A Short Summary of Empirical Studies**

<b>Study granularity</b>	<b>Methods</b>	<b>Types of Information</b>	<b>References</b>
a. Social Units			
Individuals	Protocol Analysis	Process	Akin (1981), Ullman (1987) Goel and Pirolli (1989)
	Retrospective interviews	Process	Waldron & Waldron (1987)
	Personal Construct Theory	Domain	Boose (1979)
	Protocol analysis and interviews	Usability of tools	Piela, et al (1991)
Small Groups	Participant-observer	Process	Bucciarelli (1988), Hales (1989)
	Direct Observations	Modes of face-face interaction	Tang (1989), Leiffer (1991)
	Consensus	Process	Krasner & Curtis (1988)
	Use of shared space		Tang (1989) Stefik (1987)
	Retrospective Interviews	Process and domain	Waldron & Waldron
Large Organization	Surveys	Information use	Majcher (1991)
	Interviews	Organizational structure & information integration	Clark & Fujimoto (1991) Takeuchi and Nonaka (1986)
	Use of KB tools		Stomph- Blessing (1991)
	Participant-action	Organizational and work	Whyte (1991)

flow

Information use and access Majcher (1991)

Multiple organizations	Surveys Interviews	same as above but for cross organizational, cross cultural, and cross national studies	Clark & Fujimoto (1991)
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b. Knowledge Units

Specialized knowledge (single domain)	Personal Construct	Domain knowledge	Boose et al.
	Natural Language Analysis of documents	Domain knowledge Thesaurus	Evans (1991), Monarch (1992)
	Concept networks creation through interviews	Domain knowledge	Skuce (1990)
Integrated Product Knowledge (multiple domains)	Need to use multiple methods		