Role of Empirical Studies Understanding and Supporting Engineering Design

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Background

Study of design and norms for designing dates back 2000 years when Vitruvious first wrote his book on architectural design and prescribed what a designer *ought* to know and how he/she *ought* to behave. 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. Nowadays, there are two distinct schools of design: a prescriptive and a descriptive school, the former being the most prevalent in recent literature. Some of the main concerns raised for some time in the descriptive school of design, can be expressed in the following questions:

- What do we know about what design 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?

A substantive move towards observational studies, however, has yet to take hold in the design engineering disciplines in any significant fashion. In general, there is an aversion to studying the design activity due to the time consuming nature of the process. Moreover, a persistent belief that engineering is a purely technical process, or there is a clear dichotomy between the technical and social processes. Nevertheless, there has been some interest in studying design empirically and in these cases the primary concern is methodology. Methods discussed in the design research literature to date have been derived from behavioral sciences (psychology, sociology, organizational studies) and adapted to studying the design process. A single method for studying (the activity of) design does not exist. 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.

Dimensions of studies in engineering design

Design of products takes place in a 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, chemical plants, 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, from individual actors and small groups, to organizations and networks of organizations. Studies should also be conducted concerning different knowledge units, such as studies into specialized knowledge/single domain design problems, and those concerning integrated knowledge/multiple domains.

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 discriminate 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 mature designs' case, cognizance of these attributes in previous design versions is directly applicable to the design of subsequent versions. However, evaluating the direct applicability of prior designs is a complex problem. In general, 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 reworking/revising these designs. In this sense, both new and mature designs involve information and knowledge sharing. Hence, 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.

Methods for empirical studies

A variety of methods have been used in the studies reported in the literature at various levels of granularity. Many 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.

One important point that needs to be stressed is that no single method will provide complete information either on the process or on the domain. A number of techniques have to be used in conjunction to create a robust picture of engineering design tasks and environment. Concentration on single individuals designing for mostly rudimentary 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 analyze and model data using methods from the technical and social sciences. The richness of engineering design, from a social and

technical perspective, demands that we develop integrated methodologies that are derived from a number of social sciences and technical disciplines. Some of the methods employed in studying engineering design are:
In-situ studies: Studies of industrial practice by the use of participant observer, direct observation, and other techniques in industrial settings. 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.
University-based studies: 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). In cases, where industry arrangements can be made without non-disclosure agreements, the depth of problems that can be solved is limited by the disclosure that is possible without such agreements. The other good arrangements for university-industry partnerships for design research may include the use of group summer projects at a company, coordinated co-op projects involving designs.
Domain studies: Use of knowledge acquisition tools that employ a variety of methods such as personal construct theory, interview, and ontology creation for particular domains 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 view of product information. Such studies in different industrial contexts are necessary to understand variations across industries and across national boundaries.

Contents of the proceedings

The goal of the workshop, "The Role of Empirical Studies in Understanding and Supporting Engineering Design," held on April 4-5, 2002, was to bring academics and industry people together to:

- discuss the relevance of empirical studies for engineering design practice,
- get an understanding of questions, methods and tools used by researchers,
- develop a classification of their ("their" is not obvious; the connection with tools and methods is somewhat weak) use, and
- propose methods to improve the appreciation of this work in academia, in the classroom and in industry.

As a nascent field, other goals of the workshop included creation of self awareness amongst participants to create a community in this field.

There were 23 participants including scientists from NIST, from 5 European countries, and 4 US universities and 3 industrial participants from the U.S. In four presentation sessions and two discussion sessions, the papers were presented in the following topic areas:
a) Case studies

b) Three perspectives on empirical studies
c) Insights from case studies
d) Reflections from case studies.

Session 1: Case studies
Three papers are included on case studies examining the knowledge collection and sharing in the design process, on distributed design in industry and in a classroom by Paulien Herder of TU Delft, The Netherlands, Steven MacGregor of the University of Strathclyde, Scotland, and Lois Soibelman of the University of Illinois, Urbana-Champaign, respectively. The issues raised in these papers are concerned with validity of the methods, and what knowledge, tacit or explicit, can be codified and shared. The other issue is how to generalize from these case studies in order to inform the community of an understanding of engineering design. Paulien Herder's paper deals with issues at the intersection of design processes and knowledge management. Her group studied the way information and knowledge is collected and shared among designers and organizational units in a design process. The long-term goal of this research is to improve the efficiency and efficacy of design processes by using and improving knowledge management strategies and theories within design processes. Steven MacGregor's contribution presents a range of methods used in different industries to study distributed design and a discussion on how the context of the industry impinged upon the quality of the data collected. Lois Soibelman's paper deals with the study of collaborative interdisciplinary work in a university course. The combination of instruction (lectures and discussions), action (collaborative design project), and reflection (group process critique), has proven an effective model for collaborative design education. Observation of the teams and their feedback also indicate that computer tools are not the sole enablers of true collaboration.

Session 2: Three perspectives on empirical studies
Three groups from Aachen, Germany, that collaborate on a large project, "Information Technology Support For Collaborative and Distributed Design Processes in Chemical Engineering," funded by the Deutsche Forschungsgemeinschaft (German Research Foundation) raise questions and perspectives that have guided them in using and thinking about empirical studies. The three groups represented were the work design group (Christian Foltz), process systems engineering group (Wolfgang Marquardt and Ralph Schneider), and the computer science group (Manfred Nagl and Bernhard Westfechtel). The papers in this session raise the following primary issues:
a) what is the role and scope of an empirical study?
b) what can be improved by the study?
c) what can be validated with the study?
d) how can we model design processes?
e) how can we show that tools created for support improve the performance of the processes?

Christian Foltz's contribution concentrates on the purpose of empirical studies as one of formulating or verifying a hypothesis. It raises important issues of methods of data collection and validity of the results. The primary argument of this paper is that the results of the empirical studies depend on the methods and their limitations. Any one set

of results from these studies is limited and hence requires a multiplicity of methods, as each of these results is neither completely right nor wrong. Ralph Schneider's paper deals with the interaction between empirical studies, information models and software tools. The primary hypothesis of the paper is that in order to improve the design process, the investigation of industrial processes needs to be improved, so that the underlying information models and practices of work processes can be identified. The third paper in this session is by Bernhard Westfechtel and it deals with tools that were developed for process improvement. The main observation in this paper is that the new processes did not match the actual practice. However, it was felt that the new tools could be used to improve the process. An important issue raised in the paper is that even if the right tools are built, how can their use and effectiveness be verified without industrial participation?

Session 3: Insight from case studies

The third session focused on the insights that people have gathered by performing case studies. The first contribution is from Claudia Eckert, who discusses the status of a researcher in performing empirical studies and how it affects the study in terms of sharing of information by the interviewees. An important point is made on the status of the researcher and the project champion in the company as affecting the outcome of the study and adoption of new practices. The second paper[1] is by Crispin Hales from Triodyne Corp. Hales presents a case study of a design failure of a machine tool that led to an accident and the litigation that followed the accident. The paper illustrates how the designers had failed to follow the well-known processes in design especially in evaluating safety and risk in the use of the machine. The paper points out that litigated engineering cases are a good source of research data as detailed depositions often produce good accounts of the design processes and decisions. The third paper by Kjeld Schmidt from IT university of Denmark, articulates that design organizations create and manage several sets of information, ordered into particular classifications, and that these ordering systems serve the purpose of coordinating the collaborative work. The importance of ordering cannot be overlooked in supporting any co-operative work. The fourth paper in this session, by Feinosky-Mora (then at MIT), describes a study of distributed groups working across continents. The study comprised a set of hypotheses which were tested using statistical methods and a number of instruments including participant coding sheets and interview guides. The fifth paper is by Chris McMahon of the University of Bristol). This paper makes the case that academic design is the theoretical 'worldview' of design while design in practice is a complex social activity. In the paper it is argued that it is important to study design in practice using case studies, with engineers in their domains of expertise.

Session 4: Reflections from case studies

The contributions to this session are of a reflective nature except one paper on a case study of process improvements at Ford. The first paper, by Jean Francois Boujout of the University of Grenoble, talks about the research process that their group has gone through in a collaboration experiment with sociologists. The second paper is from Ozgur Eris of Stanford University, who presents a case study of expert team interactions in the

[1] A complete paper is not included due to the proprietary nature of the case that was presented, only a summary of the process of design diagnosis is presented.

development of a product design using an iterative approach that follows an observe, analyze, intervene cycle.

The third paper is by Ira Monarch from Carnegie Mellon University, who presents a theoretical model of prototypes and boundary objects borrowed from cognitive science and sociology as units of analysis that explain the breakdowns in the communication and effectiveness of the design process. The paper by Henri Christiaans from TUDelft raises the question why studies done in design have not been used and questions whether they are relevant at all. The paper points out that most design processes observed are of students, and often result in design methodologies that are too generalized to be practical to industry and hence are used primarily in education. Design as social activity and designing in context are becoming more important, but is very hard to get a hand on in terms of generalizations that are useful to industrial practice.

Finally Morten Levin of NTNU, Norway provides an overview of perspectives from a philosophical point of view to make the argument that traditional social sciences are not the right model for studies and support of engineering design. The most appropriate approach from his perspective is one taken by action research that explicitly acknowledges the purpose of research as that of changing the state of the world in contrast to the objectivist perspectives of positivist approaches of social sciences.

Discussion session

The last session of the workshop was a discussion session based on questions raised by the participants. The primary issues addressed in this session were:

1. How do we ensure the validity and generality of the studies?
2. How can we develop support tools for industrial practice?
3. How do we share and organize our experiences concerning empirical studies in design? i.e., How do we make a community of practice?
4. How do we get industries to participate in the process?

The main conclusion that can be drawn from the papers contributed to the workshop and the discussions in the workshop was that there is a need for use of empirical studies in studying and improving design and that a community needs to be created to raise both awareness and improve the quality of tools in supporting design.

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