Management of Multi-Method Engineering Design Research

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Abstract

There is a need for a research management methodology that will utilise research methods on an individual basis and when combined in a multi-method approach. An agreed methodology would enable rapid progress in achieving agreement on the main issues within engineering design research. Researchers at the University of Glasgow have developed a conceptual management methodology, testing it on three engineering design research projects. This paper describes the methodology and presents results indicating its ability to enable rigorous triangulation of research results obtained via different methods and across different research projects forming the basis of an effective management tool.

Key words: management tools, research methods, engineering design

Classification Code: O32

1. Introduction

Increasing international competitiveness and technological advance, coupled with relentless demand for higher quality products and the existence of product liability legislation have demanded the following responses from industry:

- To exploit emerging technologies more rapidly.
- To reduce design time-scales.
- To provide 'right first time' design.
- To innovate more frequently and produce more innovative products.
- To improve the reliability of products and systems.

In their efforts to meet the above responses industry and academe have focused their research effort in developing ways to automate and guide the design process, or at least parts of the process, whilst improving the quality of the process along with its outputs. It is generally accepted that before a process can be automated it is necessary to have a clear understanding of how the process operates, how it may be improved and even how it may be optimised. Many researchers, notably Marples (1960) and Hales (1987), have researched the engineering design process as practised in specific industries and within specific industrial environments and have provided lucid descriptions of the engineering design process. There is of course a need to continue to undertake such studies since the environment within which engineering design is practised is, to say the least, dynamic.

Further, there is a need to research the particular activities exercised within the process in order to provide depth as well as breadth of understanding. For example in the past few years some work has been done in providing computer-based tools to support engineering and design at the conceptual phase (Hennessey 1994, Ullman 1995, Scrivener et al 1993). Most of these tools are based on descriptive research rather than set prescriptive (Al-Salka et al., 1998) notions of design.

The dynamic nature of the engineering design process and the need for more detailed knowledge of design activity has led to the adoption and development of various research techniques and methods. Close study of the designer's actions will, it is hoped, lay bare the thought processes underlying intellectual activities such as cognition, problem solving and creative thinking.

Within the field of engineering design research there is therefore an accepted need to employ a robust research methodology that will utilise valid research methods both on an individual basis and when

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combined to provide a multi-method approach. There is also an accepted need to be able to triangulate the results obtained from different methods employed within an individual research project or over a range of separate projects. A rigorous method of triangulation, or comparison, of results is an essential tool for the design research community. Indeed a universally agreed methodology would perhaps enable more rapid progress in achieving agreement on the main issues within design research by enabling individual researchers to replicate triangulation studies. The design research literature provides little guidance as to the nature of such a methodology but there is recognition of the lack of accepted and repeatable research methods and procedures to test proposed theories and models of design activity (Ehrlenspiel and Dylla 1993). The Design Research Group at the University of Glasgow is developing a conceptual methodology of triangulation and has tested it on three research projects. Although the methodology spans all phases of the engineering design process the initial testing has concentrated on the concept design phase. The following sections of this paper therefore describe the development of the methodology and present the results of the initial test. The results indicate that the proposed management methodology is effective in enabling rigorous triangulation of research results obtained via different methods and across different research projects. It thus provides a firm foundation for the development of an effective management tool.

2. Methodological Approaches

Valid research methods are required to permit observation of engineering design activity with the intention of collecting reliable data. The attendant difficulties surrounding research sampling and ethics, along with the issue of confidentiality and the restriction on the publishing, are all well known to the research community.

Notwithstanding these difficulties, the following methods are to the fore in design research and are now briefly reviewed:

- Protocol Studies
- Ethnographic Observation
- Historical Analysis
- Experiential Analysis

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2.2 Protocol Studies

Engineering design research has often placed credence in data taken from observation of designers working in laboratory conditions on set tasks. The number of ‘protocol studies’ has grown steadily since the beginning of the 1980s, but such programmes have tended to happen in scattered pockets of activity (Dorst 1995). Protocols involve observation of designers at work. Almost all of these studies are based on what we might call 'experimental data', gleaned from a laboratory environment.

Much design protocol research is concerned with constraining or equalising *'variables of the research equation'* (Dorst 1995). When designers work 'for real' such rational constructs do not apply. Dwarakanath & Wallace (1995) recognise the shortcomings of such experiments in saying that it is 'less representative for analyses of how design actually takes place in practice'. Acknowledgement of this caveat helps to bolster the credibility of their protocol studies, and their claim that a laboratory environment *'usefully restricts the influences on the design process'.*

A protocol analysis workshop at the Delft University of Technology in September 1994 represented the first coming together of leading researchers in this field (Dorst 1995). The resulting range of papers reveals that even though they might be based on evidence gained in 'controlled laboratory environments', there are still many ways of interpreting the results. Some papers focused on analysing the verbalisations of the subjects, taking them to be a more or less faithful reflection of their thoughts. Others concentrated on drawings made by the designers and one even studied their gestures.

2.3 Ethnographic Observation

The protocol method, with a seemingly scientific basis, has been readily accepted as a way of studying engineering design activity. More recently, and with the growing recognition of engineering as essentially a human activity, it has been proposed that the field research techniques developed in the social sciences could prove useful in helping to understand how and why design happens (Wallace and Hales 1989, Kennedy 1997).

One such social science technique is ethnographic observation. The ethnographic approach seeks to provide a written description of the implicit rules, traditions and behavioural patterns of a group. The intention is to provide a ‘rich’ or 'thick' description that interprets the experiences of the group observed

(Robson 1993). It differs from a protocol approach, most obviously, by observing an activity without having created the activity.

The researcher can take various observational stances. The participant observer enters the culture they are observing; becomes a part of the community under observation. In an engineering context, participant observation would involve researchers gaining access to companies and working as designers or with designers to get an inside view of their activities. Observation can be more or less structured; the study can become more structured as hypotheses emerge from the investigation (Kennedy 1997).

In the design research field (Bucciarelli 1994) has carried out a participant ethnographic study of an engineering firm making photo-voltaic cells. It demonstrates how the resource, time and budget constraints within the firm and the social context between designers and management have a bearing upon the activity in real life situations.

2.4 Historical Analysis

Historical analysis is the discovery from past accounts or records a description or explanation for events in the past. Historians divide data into primary and secondary sources. Primary sources include eyewitness or participant accounts, contemporary records: such as personal notes, memos, instruction manuals, and diaries, and, importantly in the case of design, the artefacts themselves. Secondary sources are summaries and reports of events by other historians or researchers.

The role of historical analysis is to provide a historical base or context for current research. Developments in design due to the introduction of new technology, for example, can be compared to developments in the past.

2.5 Experiential Analysis

Some design researchers have drawn on their own experience of designing to give explanations of aspects of design. French (1992) gives a model of the design process that he has developed through his experience of design. Pahl and Beitz (1984) propose a similar model. Design researchers are also rightly concerned about the lack of acceptance of their ideas by practising designers (Beitz 1994, Cross 1993). By involving designers in the research as equal partners it is more likely that the outcome of the research will be taken up because of the shared ownership of the knowledge produced by the research. One approach to doing this would be similar to participant observation with a designer/researcher working as a team and coming to a shared appreciation of their actions. Another, and a more common approach, is that of the ‘focus group’. Here researcher/practitioners get together in a mutually supportive environment to arrive at shared appreciation and experiences and to develop theories, and strategies relevant to these experiences.

3. Multiple Method Approaches

Quantitative data deals in numbers and statistics obtained by enumerative induction while qualitative data expresses concepts and ideas. Protocol studies deal in reducing qualitative source data to quantifiable data while an ethnographic approach yields purely qualitative results (Bryman 1992, Robson 1993). The two approaches, then, have their associated data analysis methods. Research that produces essentially qualitative results or essentially quantitative results need not be seen as opposing, incompatible disciplines. Indeed Cross (1995) and Bucciarelli (1994) both reach the same conclusion - that design is a social process - by taking, respectively, protocol and ethnographic approaches.
Multiple methods can be used in a complementary fashion to enhance interpretability. In a primarily quantitative study for example, the interpretation of statistical analyses may be enhanced by a qualitative narrative account (Robson 1993). This could explain trends and contradictions in the statistical data. Protocol studies can be seen as plausible explorations of designers' thought processes, but it must be realised that rarely are they complemented by studies of environment and social context. A mixture of the two approaches may form a reliable trace of the design activity.
The use of multi-methods brings an enhanced recognition of the need for quality methods and for them to singly and collectively to meet the following criteria of soundness (Marshall and Rossman 1994):

- Credibility/Internal validity: How truthful are the particular findings of the study? By what criteria can we judge them? The goal is to demonstrate that the inquiry has been conducted in such a manner as to ensure that the subject was accurately identified and described.
- Transferability/External Validity: How applicable are these findings applicable to another setting or group of people [designers]? This entails judgements about the relevancy of the study to a second setting.

- Dependability/Reliability: How can we be reasonably sure that the findings would be replicated if the study were conducted with the same participants in the same setting? There is a paradigmatic problem over whether the world is changing or is static. If the world is static then the problems of replicating the study disappear.
- Confirmability/Objectivity: How can we be sure that the findings are reflective of the subjects and the inquiry itself rather than the product of the researcher's biases or prejudices?

The use of multiple methods in the study of the same phenomena is known as triangulation, a phrase first used by Denzin (1989) meaning 'getting a fix from two or more places', and is intended to neutralise bias in any one approach. Denzin formulated that it was possible to triangulate in terms of multiple and different:

- data sources (e.g. informants)
- methods
- investigators
- theories

Data triangulation refers to the need to retrieve data from a number of different sources to form one body of data. Method triangulation is simply the use of multiple methods and is described as being either between-methods or within-methods. A within-method approach involves the same method being used on different occasions (repeating the same experiment at different times of year for example) and a between-method approach uses different methods in relation to the same object of study. Investigator triangulation involves the use of a number of investigators to observe the same problem thus attempting to ensure objectivity and avoid bias. Theory triangulation requires the testing of developed theories against the same body of objective data.

An important challenge for engineering design research is the triangulation of a number of protocol studies with research undertaken within a practice setting. If research findings can be examined in this way then not only will the findings themselves be seen to have enhanced credibility but also the research methods employed will be seen to be valid and reliable and therefore more readily accepted within an agreed design research strategy.

In order to test the triangulation strategy the findings from three individual design research studies were subjected to examination. Prior to starting the test it was necessary to develop a method for performing ‘triangulation’. The next section describes the method adopted by the researchers and discusses the results of a simple test of the method using data from three recently completed research studies.

5. Method and Results

The three research methods employed to undertake engineering design research, at Glasgow University, can be described as follows:

- engineering design in industry (Research Method A).
- conceptual design communication within student projects (Research Method B).
- testing theoretical model of conceptual design evaluation using expert and novice designers (Research Method C).

Therefore, Research Method A can be classified [Table 1] as an industry sited, non-participant, ethnographic observational method utilising interview techniques and spanning all three main phases of the design process (Kennedy 1997). Research Method B, on the other hand, is an academic sited, ethnographic/protocol, participant-as-observer, study centred on communication issues within the conceptual design phase of the design process (McGown and Green 1997). Finally, Research Method C is an academic/industry sited protocol study centred on the evaluation activity within the conceptual design phase (Green 1997).

Insert Table 1 here.

This classification identifies the conceptual phase of the engineering design process as being a common area of interest. The findings from each have next to be ‘triangulated’ to see if and where they overlap. Given that most of the findings from a design research project will be of a qualitative nature and presented in a text-based form it is necessary to adopt a form of data reduction that enables recognition of common findings whilst retaining a traceable connection to the original research data. The following example illustrates how the findings from three separate and independent research studies can be compared, to both identify common findings and to help validate the research findings, using data reduction matrices.

5.1 Triangulation Example

The matrices shown in Tables 2 to 4 map the relationship between needs and activities [Green 94] at two levels; Level 1 - conceptual design, Level 2a - conceptual communication activity and Level 2b - conceptual evaluation activity. It should be noted that the needs and activities listed are not exhaustive but are judged adequate to illustrate the approach. Table 2 illustrates that the three research studies presented findings related to two identified needs of the conceptual phase of the design process, namely the development of functional and structural descriptions, and three of the principal activities of the conceptual phase, namely communication, synthesis and evaluation.

Insert Table 2 here.

The above mapping process was then repeated at the conceptual design activity level, see Tables 3 and 4.

Insert Tables 3 and 4 here.

One of the most striking areas of overlap of research findings is seen to rest within the need for traceable design activity and decision making to enable effective evaluation activity. This is coupled with the need to be able to project concept design ideas into the future in order to predict the concept most likely to meet the product design specification. They reflect the common finding that, whether novice or expert, designers share a common challenge to manage uncertainty by balancing the need to minimise risk with the desire to innovate. This finding and the contingent behaviour of designer activity is supported by the following excerpt taken from an interview (Research Method A) with a consultant industrial designer talking about conceptual design evaluation:

" I think we probably did about a dozen major concepts and it was fairly - fairly clear internally here the ones that had sort of the right mix, the right feel about them. Whilst all of them probably could've been made to meet the brief, there's also this sort of unstated 'suitable for purpose', sort of - meets the perception of what we think the product should be".

6. Conclusions

This paper argues the case for a management tool supporting the adoption of a range of methods to enable research into the activities and attitudes of engineering design. It emphasises the need for an approach that checks and compares the findings from each method, this is termed ‘triangulation’. This multi-method research strategy is also placed in context via classification against the following categories:

- research methods
- research needs
- research environment
- design process phase and phase activity

This level of classification is shown to permit an initial view of the areas of overlap of various research programmes and will also support planning and management of future research projects.

A management tool is proposed to enable triangulation of research findings within an engineering design process context. At present the method allows triangulation at various levels within design phases; the next development will be to investigate triangulation between the hierarchical levels. The aim is to develop a valid management tool that supports the need for researchers to draw reliable general and specific conclusions about the nature of design from a wide spectrum of engineering design research data. In addition, the work also highlights the need for clarity regarding the definition of ethnographic and protocol studies. The research method (B) clearly spans the divide between the two and offers a third option of a ‘hybrid’ ethnographic/protocol study.

It is envisaged that the basic method presented here can and will be extended to manage the triangulation of data sources, investigators and resulting theory test results. Future work will seek to test the approach further with a growing range of research projects using a spectrum of research methods spanning all phases of the engineering design process.

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Research Needs	Research Methods	Environments		Design Process Phase		
				Conceptual	Embodiment	Detail
		Industry	Academe	C. A. S. E	C. A. S. E	C. A. S. E
Data Collection	Ethnographic Observation					
	participant					
	non-participant		B	B		
		A		AAAA	AAAA	AAAA

	Protocol Studies	C	B C	B C
	Experiential analysis			
	Historical analysis			
Model Testing *prescriptive* *descriptive*	Protocol Studies Ethnographic Observation *participant* *non-participant*	C	C	C

Note: C.A.S.E are the main activities undertaken within each phase of the design process, namely **C**ommunication, **A**nalysis, **S**ynthesis, **E**valuation

Table 1. Classification of Research Methods

Activity Needs	**Communication**	**Analysis**	**Synthesis**	**Evaluation**	**Other**
Functional description	C,B,A			B,C,A	
Structural description	B,A		B,A		
Economic description					
Usability description	B				
Environmental description					
Aesthetic description					
Other					

Table 2. Needs/Activity Matrix - Conceptual Design

Activity / Needs	Sketching ideas	Modelling ideas	Annotating drawings	Present ideas	Maintain P.D.S.	Discuss ideas	Other
Communicate with self	B		B		B		
Communicate with others	B						
Communicate with future							
Communicate with past		A					
Other							

Table 3. Needs/Activity Matrix - Conceptual Communication Activity

Activity Needs	Select Criteria	Initiate Analysis	Comparison	Prediction	Decision	Initiate Synthesis	Other
Computer based			C			B	
Clarity of Design State							
Common Links							
Projection ability				A, C			
Team Communication					A		
Traceable Design	B		C		A	C	
Other							

Table 4. Needs/Activity Matrix - Conceptual Evaluation Activity

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