Research Methods for Design Science Research: Computational and Cognitive Approaches[1]

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ABSTRACT

Research methods that claim to use the scientific approach in design research can be grouped into three categories: those founded on empirical evidence of human designing activity; those founded on axioms and their derivations; and those founded on conjectures of potentially useful processes. These three approaches are used to construct either cognitive or computational models of designing.

INTRODUCTION

Designing has long been recognised as a difficult, complex and unusual task. One of the first recorded mentions of design goes back to the code of Hammurabi promulgated around 1950 BC. Scientific endeavours have formed the basis of the technology on which much of today's society depends. They have provided the necessary theory of material behaviour and the experimental methodology to determine such behaviours. Using theories of material behaviour it has been possible to develop formal methods of analysis of the behaviour of configurations of materials (ie designs) under a variety of environmental conditions. However, science has not had the same success in providing any foundation on which to base the technology of formal design methods. More recently, it has been suggested that designing in its fullest sense maps well onto abductive processes, which helps explain why it is so difficult to formalise it. In addition to its abductive nature designing is situated: ie designing cannot be predicted since decisions to be taken depend on where the designer is at any particular time and what the designer perceives the situation to be when (s)he is where (s)he is. We will use the word "designing" to denote the act and the word "design" to denote the results of the act, to avoid confusion.

[1] Parts of this paper were presented at the ANZAScA Conference, Sydney, in November 1999.

Computational processes which support designing do not necessarily require any theoretical foundation and are restricted to some subset of the totality of the activities of human designing. This lack of a need for any theoretical foundation provides enormous flexibility when sourcing computationally implementable ideas, which may support designing.

More recently, experimental methods have been developed that allow for the study of human designing behaviour. These have been largely based on protocol analysis methods. The results of such studies are only now beginning to emerge and are providing stronger foundation on which to base the development of theories, models and methods of designing.

RESEARCH METHODS

Research methods that claim to use the scientific approach in design research can be grouped into three categories:

(i) those founded on empirical evidence of human designing activity;
(ii) those founded on axioms and their derivations; and
(iii) those founded on conjectures of potentially useful processes.

This third category can be broken into two further subcategories:

(a) conjectures based on analogies with perceived human designing processes, and
(b) conjectures based on analogies with other processes (which are clearly not human designing processes).

Whilst design science[2] strives for a theoretical foundation, its utility lies in its ability to use design computing and design cognition to represent both designing situations and designing processes using concepts of varying theoretical rigour. Those situations and processes themselves need not necessarily have any such theoretical rigour. Of primary importance is the teleology of the research endeavour. Is it to develop a theory of designing, is it to develop a model of designing, is it to develop methods for designing, is it to describe and represent the act of designing or is it to represent the results of designing?

The *Shorter Oxford English Dictionary* defines “theory” in a number of ways:

1. a scheme or system of ideas or statements held as an explanation or account of a group of facts or phenomena;

[2] *Design science* is the scientific study of designing.

2. a hypothesis that has been confirmed or established by observation or experiment and is propounded or accepted as accounting for the known facts;
3. a statement of what are held to be the general laws, principles or causes of something known or observed;
4. systematic statement of the principles of something; and
5. a hypothesis proposed as an explanation, hence a mere hypothesis, speculation or conjecture ("theory" used loosely).

It is hard to claim that a theory of designing could satisfy any of the first three of these definitions since insufficient is known and agreed upon about the acts of designing to provide details of the phenomena to be accounted for. Thus, a theory of designing is likely to belong to either the fourth or fifth definitions of theory. However, one general design theory clearly fits within definition 4 of theory, whereas the vast majority of theories would best fit into definition 5, ie speculation or conjecture.

"Model" is defined in a number of ways as:

1. representation of structure; and
2. style of structure

Whereas "method" is defined as:

1. procedure for attaining an objective;
2. procedure adopted in any form of mental activity;
3. a way of doing anything; and
4. a systematic arrangement as in a disposition of things according to a regular plan.

Finally, the *Shorter Oxford English Dictionary* defines "description" in a number of ways:

1. the action of setting forth characteristics; and
2. the combination of qualities or features that marks out a particular class.

EMPIRICALLY-BASED DESIGN RESEARCH

Empirically-based design research uses the experimental paradigm in which experiments are set up and then data is collected and analysed to produce a set of results. These results are then used as the basis of either the development of a hypothesis or the confirmation of a hypothesis about designing. Typical approaches to empirically-based design research are: direct observation of the results of designing; surveys of designers' perceptions; and protocol studies of individual and collaborating designers designing. New protocol analysis methods have been developed and are being applied to produce novel results

concerning the behaviour of designers as they are designing that has significance for the development of computational tools for designers.

Protocol analysis of designers

Protocol studies are a means of obtaining data from verbal utterances. There are two basic approaches: the concurrent or “think aloud” method and the retrospective method . In the concurrent protocol designers are asked to "think aloud" while they are designing (Ericsson and Simon 1993, Gero and Tang 2000). While designers are designing they are video- and audio-taped. The designer's verbal utterances are transcribed. The transcription is then used to develop a coding scheme(Gero and McNeill 1998). The transcription in then coded and finally analysed. An increasing number of possible analyses. In the retrospective protocol the designer does not talk during the design session but is videotaped. The designer is shown the videotape immediately after the session finishes and is asked to think aloud about what he or she was thinking during the designing process while the tape in running. This is then videotaped and used as the basis for the transcription, etc. The steps are listed below:

taping
transcription
code development
coding
analysis

The results of such studies provides grounded insight into the behaviour of designers as they are designing. These insights can form the basis of the development of computational support tools for designers.

An experimental study of designers

Designers were asked to carry out a specified design task and the "talk aloud" method was employed. Each designer was videotaped and a rich coding scheme was developed based on both design theory and the need to accommodate the data in the transcription. The development of the coding scheme is a crucial aspect of the protocol analysis method. Considerable detail about various aspects of designers' behaviour can be determined using the protocol analysis methods. Figure 1 shows the spectrum of design event lengths across a typical design session. What is surprising in these empirically-determined results is the very short duration of each design event. Without experiments with human designers such information would not become available.

FIGURE 1 HERE

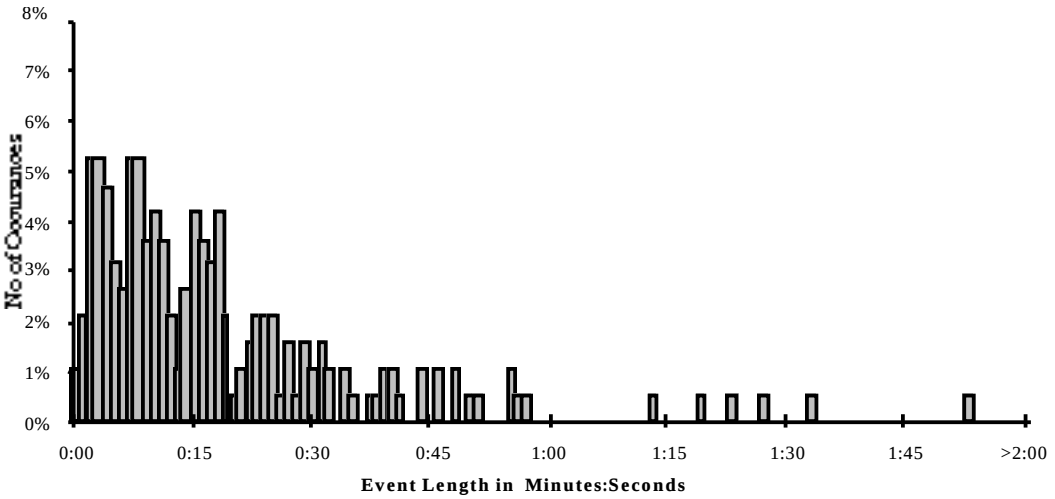

Figure 1. Spectrum of coding design event lengths (Gero and McNeill 1998).

AXIOM-BASED DESIGN RESEARCH

Axiom-based research produces models of design through the identification of a set of axioms and the logical consequences of the axioms. This approach to design science research involves:

(i) specifying relevant axioms
(ii) deriving logical consequences of the axioms

mapping the axioms and their consequences onto a particular domain to derive new results.

For example, an axiomatic logic-based shape representation allows for the uniform representation of shapes with or without curved boundaries, the consequences of which are representations of complex shapes that can be manipulated with logical implications (Damski and Gero 1996). Consider the universe of discourse as the space defined in Figure 3. The axiom is that the space can be divided into two complementary spaces.

The following can be defined or inferred from the axiom:

- a predicate hs(a) is defined for the halfspace a and -hs(a) for the halfspace a'
- hs(a) is defined as True and -hs(a) as False
- a volume V is the logical difference of hs(a1), hs(a2),..... hs(an)
- a shape S is the logical addition of V1, V2, V3,..... , Vm.

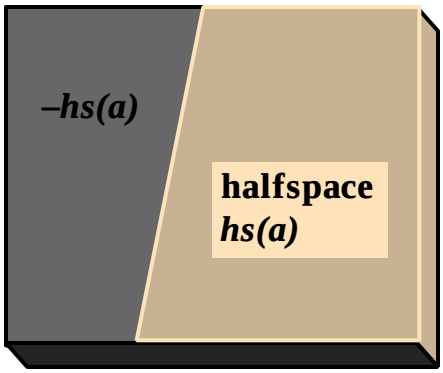

FIGURE 2 HERE

Figure 2. A space divided into two halfspaces, labelled hs(a) and -hs(a).

Consider the painting in Figure 3 which shows a girl with a hat, along with a set of labelled halfplanes. The representation of such near arbitrary shapes is computationally extremely difficult if the designer wishes to reason further about them. The axiomatic approach described here can handle these shapes.

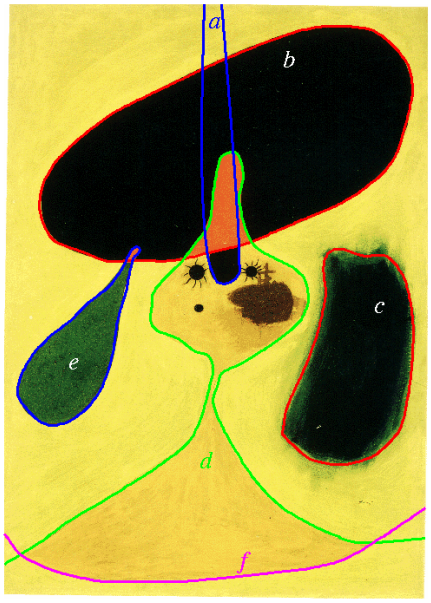

FIGURE 3 HERE

Figure 3. Miro's Girl in a Hat.

The girl's hat is defined by:

hs(b) ∧ -hs(c) ∧ hs(f)

The girl's head and body is defined by:

-hs(c) ∧ hs(d) ∧ -hs(e) ∧ hs(f)

From such representations we can carry out a variety of design-related shape and topological computations even though the original shapes are difficult to represent numerically and even more difficult to manipulate.

CONJECTURE-BASED DESIGN RESEARCH

Conjectures based research relies on identifying an analogy with other processes. This research paradigm commences with either a human process or a computational process and develops it as a specific model of a designing process. Some examples of models based on an analogy with cognitive models of designing include: case-based designing (design based on precedents); design prototypes (knowledge chunking); graphical emergence (emergence of shapes, objects, semantics and style from drawings); designing by analogy (between domain analogies in particular); and qualitative reasoning in designing (qualitative representation and reasoning about shapes and spaces). The development of models of designing need not rely entirely on cognitive studies of designers, there is the potential to identify an analogy with computational processes and apply them to a design domain. This type of research borrows heavily from computing fields such as artificial intelligence to produce specific computational models of design; for example: evolutionary systems (genetic engineering and co-evolution); and neural networks (emergence models).

Shape emergence

Emergence is the process of making properties, which were previously only implicit in a representation, explicit. In the visual domain it is a common human process (Gottschaldt 1926, Granovskaya et al 1987). From the work of the Gestalt psychologists and more recently that of the cognitive psychologists, it is possible to construct computational models of shape emergence based on concepts drawn from their research. Humans appear to distinguish foreground from background in their reading of shapes. In order to emerge shapes which were not previously represented a process which manipulates the foreground and background can be constructed. What is done is to take the primary or originally represented shape and "unstructure" it so that it now becomes part of the background, producing an image composed of unstructured shapes only. A structuring process is then passed over this background to emerge foregrounds which may include both the primary shape and newly represented shapes. Gero and Yan (1993) have developed such a process based on a new representation, infinite maximal lines, along with a structuring process.

The concepts behind shape emergence can be extended to emerge shape semantics, where the shape semantics are derived from visual patterns of shapes. Since these patterns were not originally represented they are emergent when there is a computational process which

can find and represent them. From seeing drawings, various visual patterns are perceived by the human viewers; designers can find different visual patterns from what was intended to be drawn. The newly discovered visual patterns may play a crucial role in developing further ideas in the same design if the designer is willing to adapt the visual pattern which was not there at the moment of drawing (Suwa et al 1999).

DISCUSSION

Empirically-based design research looks like experimental cognitive science research. Axiom-based design research looks like mathematical/logic research. Conjecture-based design research looks like some theoretical engineering research. Thus, research into designing spans a range of research paradigms. What both the projects and the framework of paradigms imply is that design research has now reached a level of maturity that allows it to operate as the methodological basis of design science. It is one of the primary means of developing theories, models and methods of designing as a process. It uses these as a basis for the development of design tools, and is beginning to use the theories, models and methods as a basis for teaching (although this has not been presented in this paper). Increasingly conjectures are based on empirical results. Novel concepts from cognitive science with evidentiary support from empirical studies such a treating designing as being situated continue to open up possibilities for doctoral research.

Acknowledgments

The projects described here have been supported by a number of grants from the Australian Research Council. Computational support has been provided by the Key Centre of Design Computing and Cognition. The projects described in this paper have been carried out with Jose Damski, Han Jun, Vladimir Kazakov, Tom Mc Neill, Terry Purcell, Thorsten Schnier, Masaki Suwa, Michael Tang and Min Yan.

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WORD COUNT TO HERE: 2,350

BIOGRAPHICAL NOTE

John Gero PhD is Professor of Design Science and Co-Director of the Key Centre for Design Computing and Cognition at the University of Sydney where he is also the Head of the School of Graduate Studies and Pro-Dean in the Faculty of Architecture. He is the co-author or editor of 30 books and over 400 published papers in the fields of design science and computer-aided design and has given over 300 presentations at conferences, universities and research institutions.

He has been a Visiting Professor of Architecture, Civil Engineering, Mechanical Engineering, or Computer Science at Columbia University, Strathclyde University, INSA-Lyon, University of California–Los Angeles (twice), Carnegie Mellon University, University of California–Berkeley (twice), Loughborough University of Technology and Ecole Polytechnic Federale de Lausanne. He is the recipient of numerous awards for his research. He has supervised 30 doctoral students and carries on a consulting practice.

BIOGRAPHICAL NOTE WORD COUNT: 145