Computer-Aided Design 41 (2009) 136–146

Contents lists available at ScienceDirect

Computer-Aided Design

journal homepage: www.elsevier.com/locate/cad

Impact of CAD tools on creative problem solving in engineering design

B.F. Robertson [a,*], D.F. Radcliffe [b]

[a] Catalyst Research Centre for Society and Technology, School of Engineering, University of Queensland, 4072, Australia

[b] School of Engineering Education, Purdue University, IN 47907, USA

ARTICLE INFO

Article history:
Received 18 August 2006
Accepted 2 June 2008

Keywords:
CAD
Creativity
Conceptual design

ABSTRACT

This paper presents the results of a survey of CAD users that examined the ways in which their computational environment may influence their ability to design creatively. This extensive online survey builds upon the findings of an earlier observational case study of the use of computer tools by a small engineering team. The case study was conducted during the conceptual and detailed stages of the design of a first-to-world product. Four mechanisms by which CAD tools may influence the creative problem solving process were investigated: enhanced visualisation and communication, circumscribed thinking, premature design fixation and bounded ideation. The prevalence of these mechanisms was examined via a series of questions that probed the user's mode of working, attitudes, and responses to hypothetical situations. The survey showed good support for the first three mechanisms and moderate support for the fourth. The results have important implications for both the users and designers of CAD tools.

1. Introduction

Creativity is increasingly recognised as being important to engineers [1–3]. Creative problem solving is valuable at any stage in the design process, but it is of critical importance in the conceptual design stage. While a significant amount of research has been conducted into ways to improve interface design to assist in producing creative output, it has been noted that commercial CAD tools can lag one or two decades behind the first demonstration of a new idea in this area [4]. For now, most CAD users must suffice with using the same design tools and interface for conceptual design as they use for detailed design. Meanwhile, the growing competitiveness of the commercial sector and the increasing complexity of systems is creating greater pressure for innovative solutions [5], and hence a greater need for creative performance.

There is growing evidence that the ubiquitous CAD tools that design engineers use in their everyday work are influencing their ability to solve engineering problems creatively, in both positive and negative ways. The positive factors that are most frequently cited (often by the CAD vendors themselves) are that 3D CAD allows a designer to visualise and to "play" [6,7] with new ideas, that the increased efficiency of the design process allows the designer to spend less time on detail and more time on being creative [8], and that CAD promotes communication between colleagues, enabling richer "group creativity" [9].

While these positive effects are generally accepted and fairly self-evident, the negative effects are more nebulous. Most of the evidence for the negative impact of CAD tools on creativity is anecdotal or indirect, such as that provided by Hanna and Barber [10], Mitchell [11], and Lawson [12]. Lawson argues for the need for an empirical study on the issues. Carkett's [13] ethnographic study identified a broad range of barriers to creativity in design, but was not specifically focussed on CAD. There have been attempts to make the CAD tool itself exhibit "creative" behaviour that have had some success within well-structured problems but this approach has not had widespread application in practice [14–16].

This paper fills the need to build on these studies with an empirical exploratory study of the influence of engineering software on creative problem solving in design, focussing on the use of 3D mechanical CAD. An initial, qualitative stage of the research is discussed in the following section, followed by the design of an extensive online survey and then the findings.

Before exploring the topic further, it is necessary to explain what we mean by the term "creativity". Although it is a common, everyday term, it is difficult to define creativity scientifically. A study by Taylor [17] uncovered more than 60 definitions of creativity in the literature. In this paper, "creativity" is used as shorthand for creative problem solving in engineering design. The meaning it conveys is different to the way in which the term is used in fields such as art, where aesthetics and novelty are important. In the context of this paper it refers to ideas or concepts which are both novel and useful [18], or unexpected connections between seemingly unrelated ideas, concepts, or solutions.

* Corresponding author. Tel.: +61 428741623.
E-mail address: brett.robertson@uq.edu.au (B.F. Robertson).

0010-4485/$ – see front matter © 2009 Published by Elsevier Ltd
doi:10.1016/j.cad.2008.06.007

2. Qualitative study

The aim of this initial stage of the research was to gather rich descriptions of how CAD and other computer tools are used in practice. This case study was done using participant observation through being embedded in a small engineering design team for an extended period. The methods and results of this stage are explained more fully by Robertson and Radcliffe [19].

2.1. Case study engagement

Project Omega involved the design, construction, testing and launch of an experimental rocket engine for an international client. The design and development team of six engineers operated in a project environment where innovation, flexibility and speed were essential for survival. The team, which worked in a very easy-going manner with a minimum of formality, has a track record of developing creative solutions in a relatively immature technology area. The innovative nature of the work on this project, the critical time pressures they were under and their very limited resources increased the need for a creative outlook within the team. The strong personalities of some of the design team tended to exaggerate the sense of a creative dynamic in the project.

Half of the design team used an advanced 3D CAD package (3 out of 6) while the others used a more basic 2D CAD package, but for a much smaller proportion of their time. Thus there was an opportunity to compare the differences in work habits between the two groups, and to examine the effects, both positive and negative, of CAD on creativity.

One of the authors was a participant in the Project Omega design team for two extended periods across the first three years of the project. Initially he was involved in design tasks including the extensive use of CAD tools for a period of 12 months part time. Later in the project he spent 8 months full time as a member of the team responsible for detailed design and sub-contracting the manufacturing effort.

During these two periods of engagement, field notes of observations and reflections of the practice of the team were made. These were complemented by informal interviews and discussions with other members of the design team. No attempt was made to measure the creativity or creative product of the design team members during the case study. Aside from the difficulties involved in measuring creativity [20], to do so would have been disruptive to the design team at a crucial time. Rather, the focus was on identifying the presence or absence of barriers and enablers to the creative process. The emphasis was on the mechanisms by which this might be occurring, rather than how much it is occurring.

2.2. Case study findings

During the case study, a series of observations known as "critical incidents" were collected to examine the effects that CAD use was having on the creativity of the designers. Four categories of effects were extracted from these incidents: enhanced visualisation and communication, premature fixation, circumscribed thinking, and bounded ideation.

1. *Enhanced visualisation and communication*. As might have been expected, the use of CAD in the project greatly enhanced the ability of the team to visualise and communicate their ideas. This point is frequently espoused by proponents and developers of CAD systems. It is indeed true that CAD has created something of a revolution in the implementation and communication of new ideas. While this did not address the generation of these ideas in the first place, it did undoubtedly assist the creative process as a whole. However, there were some concerns about the modes of communication that were used. It was observed that having several people crowded around a computer monitor was not the most ideal situation for brainstorming and idea evaluation. Furthermore, when a detailed CAD model is displayed, it can convey an illusion of completeness that tends to discourage creative thought in a group situation.

2. *Circumscribed thinking*. The functional capability of the CAD tools often limited the solutions available to the team. Although a large amount of effort has gone into continuously improving the functionality of CAD tools, it is possible that they may never match the imaginative capabilities of designers. A more serious problem may be that the design ideas were limited not only to what is possible with a given tool, but what is easiest. In the case study, time pressures often forced the designers to generate intended designs in the easiest way possible. At times, this pushed design decisions away from what best met the design criteria to what was easiest to generate with the tools available. Thus the ideas and thinking of the designer are circumscribed by the CAD tool's capability. This "negative" circumscribed thinking is potentially a barrier to the creative process [12]. Another dimension to this phenomenon was observed in the later stages of the case study investigation. As the proficiency of the 3D CAD designers grew, the forms grew more complex, and the design philosophy moved away from one of simplicity and sufficiency and towards one of excellence and even perfection. This "positive" circumscribed thinking, which occurred when the functionality of the tool allowed the designer too much creative freedom, can introduce unnecessary complexity into the design and waste resources.

3. *Bounded Ideation*. Using a CAD tool for a large proportion of the working day was not always the most conducive environment for idea generation. It was observed on Project Omega that more ideas were generated by the team members who did not use the advanced 3D CAD tools. Furthermore, the best environment for idea generation tended to occur away from computers, in small meetings, characterised by large amounts of sketching and discussion. It seems that the mundane nature of drafting on a computer, exacerbated by technical problems and software bugs, is a distraction from the actual process of designing, and especially from idea generation and creative problem solving. The intrinsic motivation of the designer has a central role to play in promoting creativity [18].

4. *Premature fixation*. As the CAD models became more detailed during the course of the project, there was a strong disincentive to make major changes to them. The models developed a kind of "inertia" as they become more detailed and concepts become frozen, a phenomenon known as design fixation [21]. In the case study, a resistance developed to ideas which would lead to too many changes to the model itself or to its underlying structure. The resistance was present even if these changes would solve numerous problems or make other improvements such as reducing overall project risk. The potential benefits of incorporating new ideas into an embodied concept are perceived to exceed the cost of propagating these ideas through a CAD model. This issue would be of little consequence if all of the creative processes could be situated at the beginning of a design effort. However, in any situation in which a highly structured development process is not possible, this is not the case. This occurs in what some describe as "messy", real-world problems [22], where compressed timelines, unpredictable external changes or unprecedented requirements necessitate a more flexible approach known as deferred fixation.

These preliminary findings provided the structure and focus for a subsequent survey of a large number of CAD users, as described in the following sections.

3. Survey design

The primary aim of the survey was to discover whether the phenomena identified in the case study were experienced more generally by engineering designers who use CAD. The case study involved the collection of in-depth, qualitative data, and the survey provided the opportunity to test those findings in other situations. It was designed to establish that the experiences from the case study are not an isolated product of that particular combination of project, environment, and people, but are transferable to other projects and contexts. By asking open-ended questions to a broader audience of CAD designers, the survey also provides the opportunity to identify whether there are any mechanisms that were missed in the case study.

The survey was targeted specifically at engineering designers who regularly use mechanical 3D CAD packages in their work. Responses were sought either through personal contacts, or by posting messages on online forums where specific CAD programs, CAD generally, or engineering design are discussed. Using this method, about one in ten of those who view the forum message responded to the survey. The survey questions (excluding the background questions) are shown in the Appendix of this paper.

The style of the questions in the survey was conversational and colloquial, so as to establish a personal connection with the respondents, something that is often lacking in a medium that can be dry and impersonal. Where possible, specific details and actual experiences were used in an attempt to prompt the respondent to refer to their own experiences, rather than resorting to their beliefs and overall "impressions", which have been shown in the social sciences to be unreliable [23].

Questions 1–11 of the survey (not shown in the Appendix) ask about the background of the respondent and the type of work they do. These questions have two purposes. Firstly, they allowed us to establish that the respondents are being drawn from a sufficiently diverse range of sources, and identify any unexpected biases. The second purpose of these questions was to test whether any of the variables relating to the demography, geography, industry, CAD package or experience of the respondent have any significant impact on the responses in the rest of the survey.

Questions 12–15, which related to *visualisation and communication*, begin to examine the findings from the case study. These questions examined the frequency of use of five different modes of working in four situations. The "modes of working" are:

- Working directly with a CAD program.
- Using output from a CAD program such as printouts or screenshots.
- Free hand sketching.
- Verbal discussions.
- Traditional drawing boards.

The four situations are as follows:

- Communication of an immature design concept.
- Communication of a mature design concept.
- Visualisation of an immature design concept.
- Visualisation of a mature design concept.

These variables helped to bring some detail to the analysis of the ways in which CAD is used in the workplace.

The next two questions, which examined *circumscribed thinking* and *bounded ideation*, each invite the respondent to select one of five different options. In both cases, the first response is strongly positive in favour of the benefits of CAD, the second response is somewhat positive, the third is neutral, the fourth is somewhat negative, and the fifth is strongly negative. The sixth response is for the respondent to select if they cannot relate to any of the other responses, and there is an open request for further comments at the end.

The final section of the survey, containing Questions 18 and 19, concentrated on *premature fixation*. A specific scenario was presented, which was derived from a situation encountered in the case study. The scenario was presented in a very conversational style, rich in detail. The first of the questions establishes whether there is a bias towards the precursors of premature fixation and the second establishes whether those conditions do in fact lead to premature fixation. The respondents were also given the opportunity to give an open-ended response if they cannot identify with any of the options provided.

A pre-trial of the survey was conducted with a small number of respondents ($n = 15$) to try to identify any problems with the survey instrument before it was released to a wider audience. Several minor changes were made before the final survey was released, but no major problems were found.

4. Survey results

A total of 255 people responded to the survey, 43 of whom did not complete the whole survey. The remaining 212 responses were used for the analysis. Overall, the survey provided some surprising and some expected results. Evidence was found that supported some, but not all of the case study findings. Each of the following five sections describes and explains the overall results from each of the sections in the survey. Some other interesting findings, derived by looking at subdivisions of the population, are also presented.

4.1. Background and demographics

The background and demographics of the respondents in the survey are shown in Figs. 1 and 2.

Results from the background questions gave a predictable picture of the demographics of the CAD users who responded to the survey. The typical respondent was male, was trained to undergraduate level, had more than 7 years of experience as a designer, and worked in a small team. While a variety of CAD packages are used, the programs SolidWorks and ProEngineer accounted for two thirds of the respondents. A wide range of work activities are performed, including both conceptual and detailed design of products both with and without precedents. There was a fairly even distribution across different industry sectors with the most frequent being consumer goods and industrial machinery. Respondents were located in 31 different countries, with just over half being from USA.

These respondents included a higher than expected portion of experienced users (88% had 4 or more years of experience). The vast majority also indicated that they use CAD either constantly or most of the time. It would appear that experienced, constant users are more likely to visit online CAD forums and take the time to fill out surveys. Many respondents showed with their comments that they were keen to pass on the lessons they had learned from their years of experience. There was a much lower percentage of people using the AutoCAD family of products as would have been obtained from a random sample of CAD users. This lower rate of participation was expected, as the survey was targeted towards 3D mechanical CAD users and many AutoCAD users (anecdotally at least) seem to use it as a 2D tool.

4.2. Communication and visualisation

The results of the survey confirm the case study finding that CAD is a very useful tool for communication and visualisation. However, some subtleties emerged from the data. In particular, it is interesting to compare the relative use of different modes of working between mature and immature designs, and between visualisation and communication. Fig. 3 compares the responses

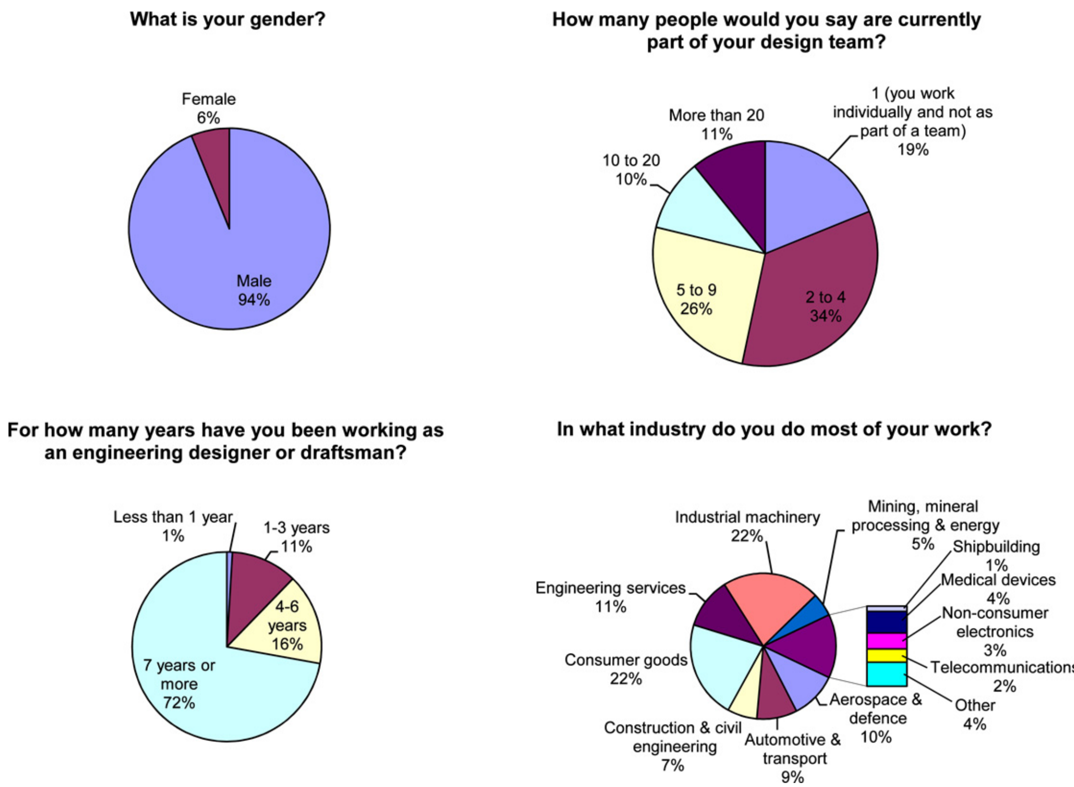

Fig. 1. Demographics of survey respondents.

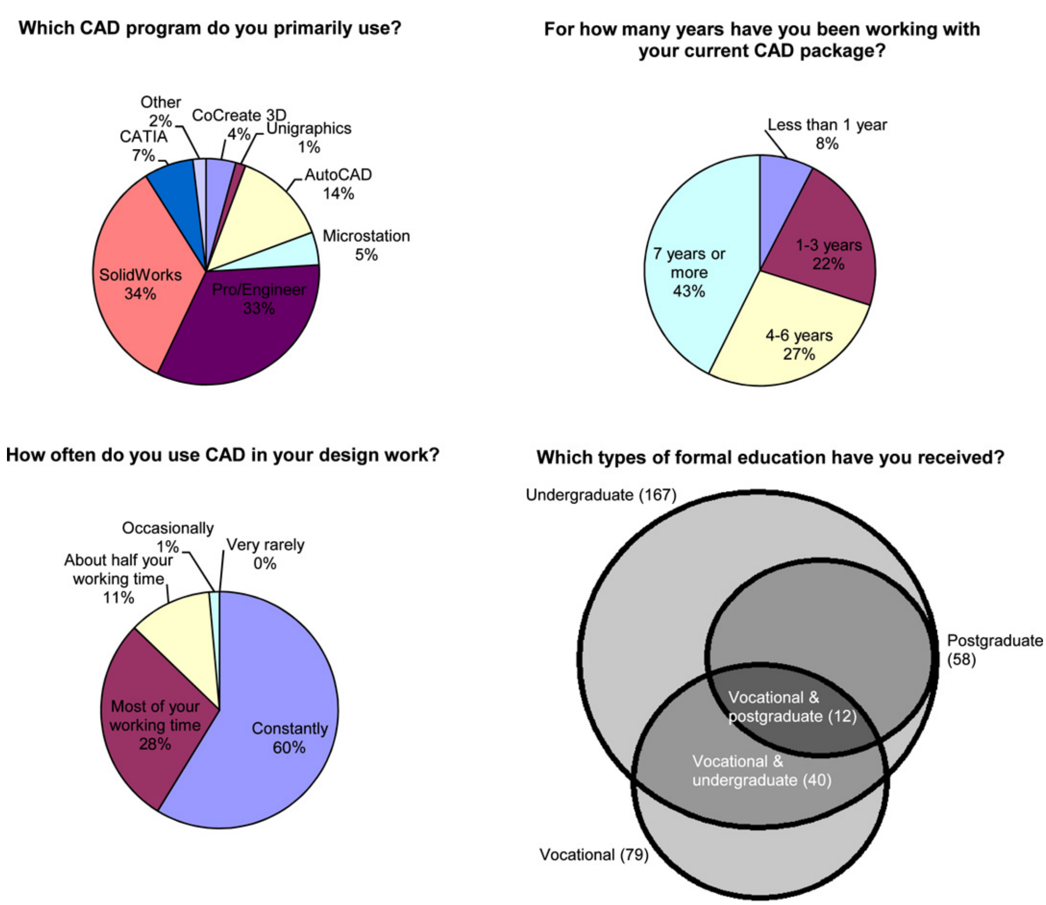

Fig. 2. CAD usage and educational background of respondents.

Fig. 3. Comparison of preferred mode of work when designs are immature or mature.

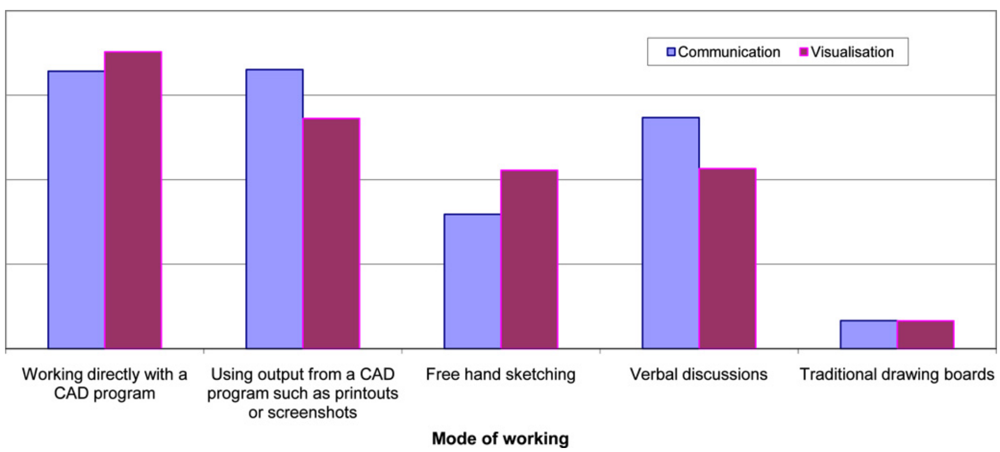

Fig. 4. Comparative use of different modes of working for communication and visualisation.

for fully developed, mature designs with immature designs, in terms of the preferred mode of working.

For immature designs, there was a lower level of CAD usage and more use of three other modes of working, free hand sketching, verbal discussions, and drawings boards. The inference is that CAD is a tool that is better suited for detailed design than for conceptual design. Several of the respondents provided comments to elaborate on the nature of this difference:

> "First of all step away from the CAD station at the beginning of the design process. STEP AWAY FROM THE MOUSE! Quickly sketching and prototyping is the way to go. Rough prototypes will show you [. . .] the merits to a certain solution quickly".

> "You will still find piles of cartoonish hand drawings with loads of pens, pencils and erasers on my desk".

> "I am afraid that I have become so used to modelling very early in the concept stage that I have deadened my ability to be a spontaneous thinker".

These comments, which support other anecdotal statements made by CAD professionals. [24], go further than the numbers would suggest. It can be seen from Fig. 3 that although the frequency of use of CAD is lower for immature designs, it is still the most frequently used mode of working. There are several ways to interpret this apparent discrepancy. One interpretation is that while CAD is better at handling mature designs than immature designs, it is still the best tool available for both tasks. On the other hand, it can be argued that the data shows that there is a tendency for users to over-use CAD, even in situations where other tools might be more appropriate, such as at the conceptual design stage. This is illustrated by the fears of one respondent:

> "I am afraid that I have become so used to modelling very early in the concept stage that I have deadened my ability to be a spontaneous thinker."

Comparing the responses for communication and visualisation, Fig. 4 shows that for visualisation there is a higher incidence of working with CAD directly and free hand sketching, and a corresponding lower incidence of using output from CAD and verbal discussions. This confirms a phenomenon observed in the case study that while sitting at a computer screen may be an acceptable mode of viewing a design for an individual, it is not the best mode of communication to groups of people. One inference of this result is that CAD use encourages individual work over group work, and individual problem solving over group problem solving.

4.3. Circumscribed thinking

Circumscribed thinking arises when a CAD program constrains or "circumscribes" the thinking and problem solving of the designer. In the ideal situation, a designer is constrained only by the requirements of the task and is free to express their intent on the design. When the CAD tool interferes too strongly in the design process by limiting what can be created, or by encouraging the designer to over-reach the requirements of the task, this ideal is not achieved. As shown in Fig. 5, roughly a quarter of the respondents showed (by selecting response 2) that they were not affected by circumscribed thinking, and were driven by the