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Impact of CAD tools on creative problem solving in engineering design

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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.

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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

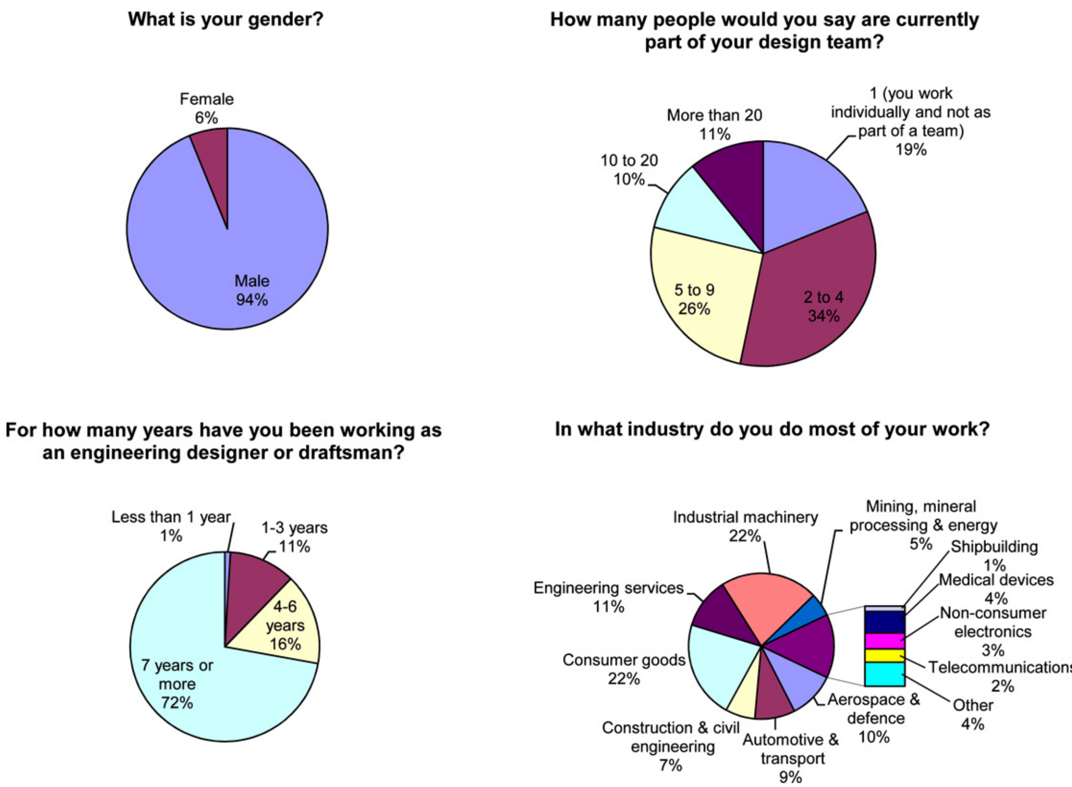

Fig. 1. Demographics of survey respondents.

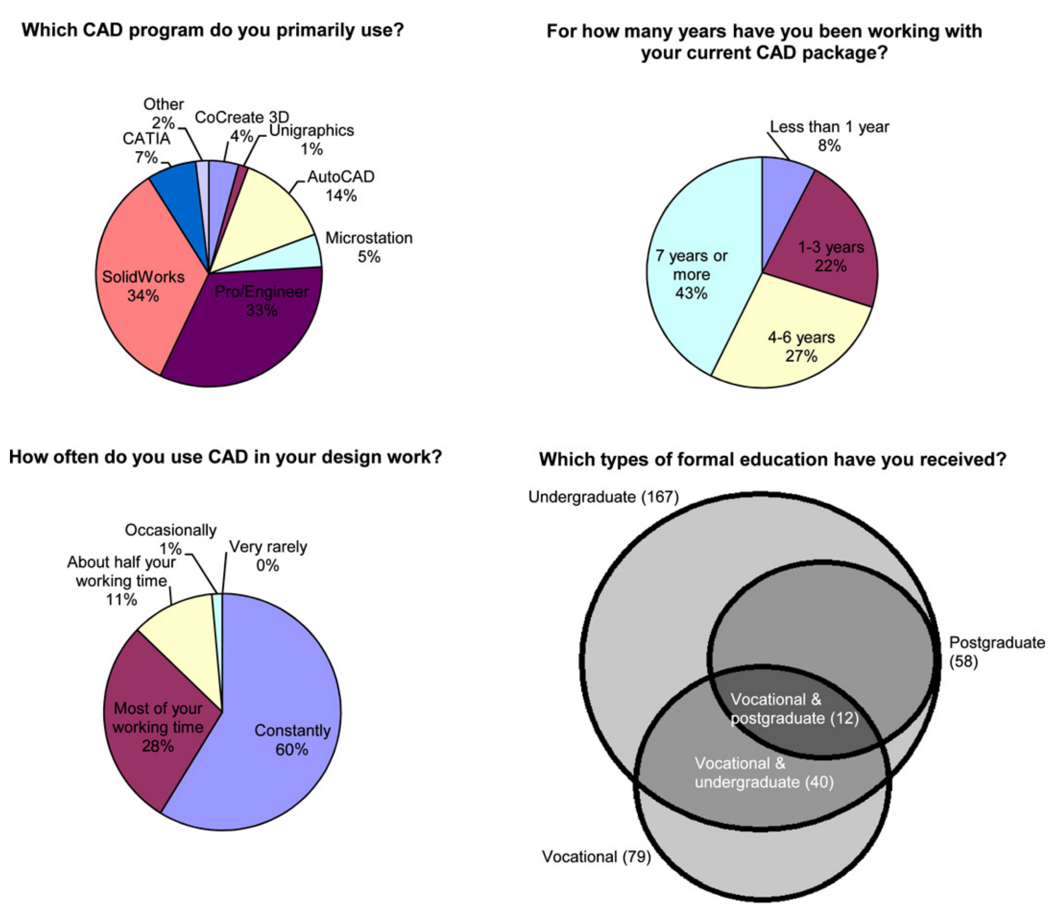

Fig. 2. CAD usage and educational background of respondents.

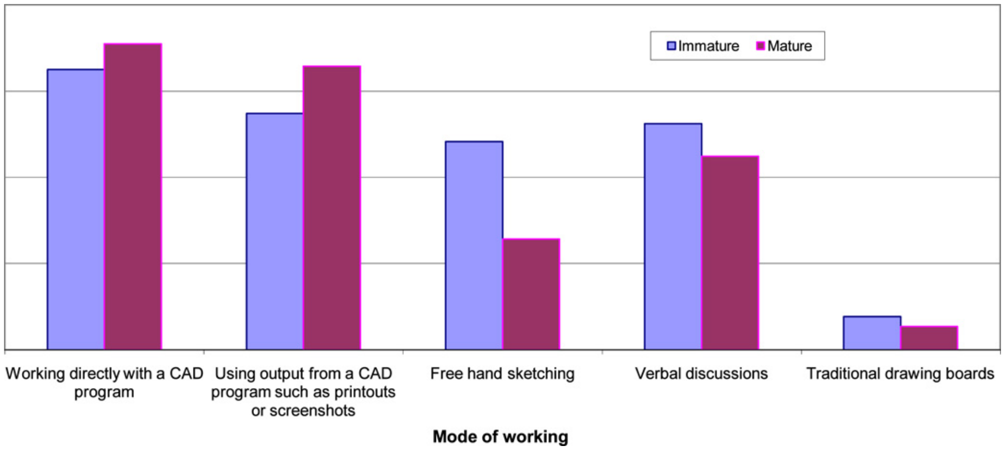

Fig. 3. Comparison of preferred mode of work when designs are immature or mature.

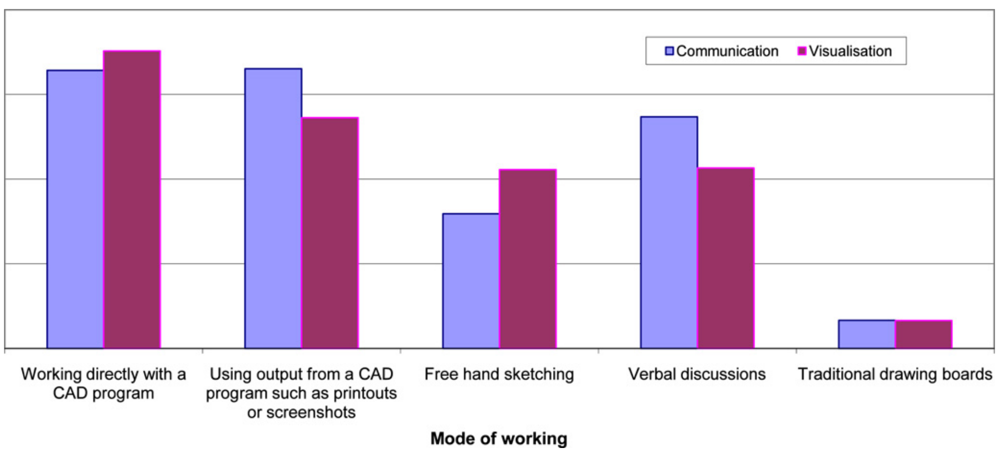

Fig. 4. Comparative use of different modes of working for communication and visualisation.

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

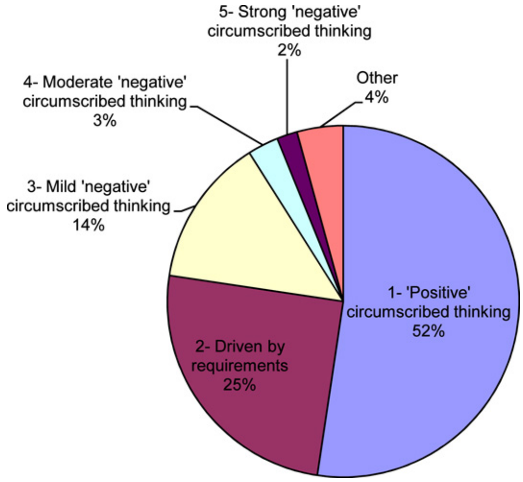

Fig. 5. Circumscribed thinking question.

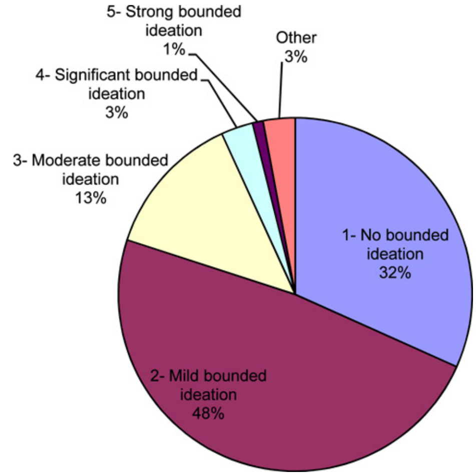

Fig. 6. Extent of bounded ideation.

requirements of the task. Just over half showed that they do become so enamoured with the power and functionality of the CAD tool that they go beyond merely satisfying the requirements and aim for "perfection". We call this *positive* circumscribed thinking.

Of the remainder, 19% admitted that the design could be negatively influenced, because of the limitations of the CAD tool or because of limitations in their ability to use it. This is reflected by responses 3, 4 and 5 in Fig. 5. Fortunately, most of the users who are influenced by this *negative* circumscribed thinking are only mildly affected.

Some of the comments the users left illustrate this phenomenon:

> "I enjoy using a CAD system that does not limit what I do — I want MY creativity to be the outer limit, not what I'm able to create in the CAD system".

> "Of course the tools you use effect the way you design — give someone a black pencil and they will come up with different ideas than if they draw with a red pen. [. . .] I can walk through a store and frequently tell what software certain products were designed in. [. . .] The methodology you use changes the way you think about a problem. It is blatant".

This suggests that circumscribed thinking, which was observed qualitatively in the case study, does occur in the wider CAD community. Whether or not it always results in undesirable outcomes for the design effort is beyond the scope of this study to determine.

4.4. Bounded ideation

Bounded ideation can occur when the constant use of CAD under stressful conditions negatively affects the motivation, and hence the creative potential, of designers. The survey data indicates that most CAD users are not affected, or are only mildly affected, by this phenomenon (Fig. 6).

Responses 1 and 2 were by far the most frequent. However, the observation that 17% of respondents may be affected by periods of low motivation is still cause for concern. This is not a desirable state to be in for any sort of work, particularly for engineering design, where creativity is an important attribute. An alternative explanation is that the type of users who responded to the survey were predisposed towards answering towards the top end of the scale, which may have skewed the results. This quote illustrates the feelings of one respondent:

> "[My level of motivation] will depend on my mind set on any given day, [. . .] there are some days that nothing puts joy in my life and my CAD work suffers on those days no matter what my software is. Mostly the first [response applies] but some of all the others are there".

4.5. Premature fixation

In the case study, it was observed that when a large amount of detail and interconnectedness is built too quickly into a CAD model, this can lead to designers becoming prematurely fixated on certain design solutions. The survey data suggests that this is a real, but not a widespread, problem amongst CAD users.

The first of the two premature fixation questions examined the precursors of premature fixation, which occur when a high level of structure is built into a CAD model early in the design process. The results for this question (Fig. 7) show that the main precursors of premature fixation seldom occur. Only 13% chose the option that indicated they would prefer the immediate implementation of a highly structure model. Most respondents (45%) opted for the delayed implementation of a highly structured model. This result implies that the features of the packages involving parameterisation and interconnections are avoided when CAD is used in the earlier stages of design, and are only used later on when the concepts become more mature. The second most common response for this question was for the immediate implementation of an unstructured model. The pattern we can see emerging is that when CAD is used in the early, conceptual stages of design, it is effectively used as a drafting tool, for computer-based sketching. It is only in the later stages that it is used in the way that the CAD developers had intended, as a fully-fledged "design" tool.

The second question addressed the issue of premature fixation more directly, by testing whether the phenomenon can be observed in a situation in which the "ideal" conditions for premature fixation exist. The results (see Fig. 8) show that only 5% of the respondents chose the option which implied premature fixation. It is important to note that this question asked the respondent to place themselves in the situation of having chosen response 1 for the previous question, yet only 13% respondents are actually likely to put themselves into such a situation.

It is also significant that this question received the highest number of "other" responses. While it is difficult with a hypothetical scenario to predict all of the likely responses, the comments made by the respondents who chose "other", provide a valuable insight into their thinking. They were asked to make a choice between staying with an existing, detailed design model

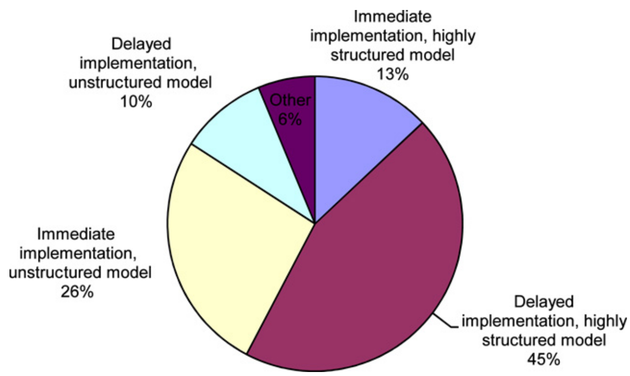

Fig. 7. Precursors of premature fixation.

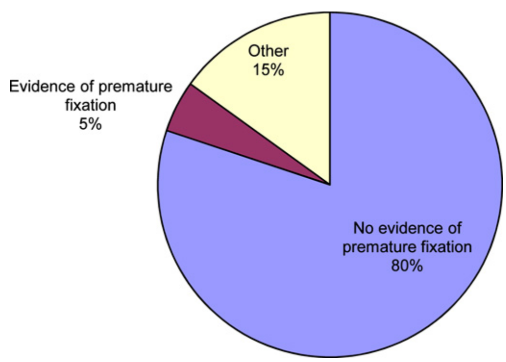

Fig. 8. Extent of premature fixation.

or making the modifications necessary to move to a newer, better design concept. The following are some illustrative examples of their responses:

> "It depends very strongly on the schedule. I would prefer to just go with the better solution, but if there isn't time to make the changes, sometimes you are just stuck with the solution you have already completed".

> "I would more likely be in the middle of the two options. I would most likely lean towards the first choice but the time I spent on the original design could sway my opinion somewhat".

4.6. *Other interesting findings*

The following sections outline some interesting results that were obtained by dividing the population into different subgroups, based on their answers to some of the questions in the background section of the survey. Two of the variables stood out as having a significant influence on the results: (1) the level of CAD experience and (2) the level of daily usage of CAD. Other variables such as gender, industry or team size did not show significant variations in the results.

4.6.1. *Effect of level of experience*

Some important differences were noted between experienced and inexperienced CAD designers. "Inexperienced" was defined as those who had worked as a designer or draftsman for three years or less. This definition was chosen because it produced the most pronounced difference in the results between inexperienced and experienced. Based on this criterion, 166 respondents were experienced and 26 were inexperienced. Table 1 illustrates some of the differences between the two groups.

In relation to circumscribed thinking, it was found that experienced designers are more likely to be driven by requirements, and not affected by circumscribed thinking. Response 2 (driven by requirements) received 19% from inexperienced users and 26% from experienced users. There was a corresponding drop in the result for Response 1 ("positive" circumscribed thinking) for experienced users. This suggests that experienced CAD users are less likely to fall into the trap of positive circumscribed thinking, and more likely to be consciously driven by requirements.

On the other hand, experienced designers may be more likely to show mild levels of bounded ideation. This group had a lower percentage for Response 1 to the bounded ideation question (down from 44% for inexperienced users to 30%) and higher for the Response 2, which exhibits mild bounded ideation. One interpretation might be that more experienced CAD users become less enthusiastic about their work as time goes by. As their motivation wanes, this may have an influence on the creative process. However, it should be noted that for both experienced and inexperienced users, the vast majority (80% in both cases) have either no, or only mild, bounded ideation.

The effect of experience was also seen in the responses to the first of the two premature fixation questions. Both of the "unstructured" responses were more popular for experienced users. This seems to indicate that experienced users are slightly more reluctant to use the full functionality of their CAD packages in terms of the parameterisation and interconnection of their models. There was no significant difference between the two groups for the second premature fixation question.

4.6.2. *Effect of level of CAD usage*

Several unexpected differences occurred between those who indicated that they used CAD constantly (124 respondents), and those that did not (87 respondents), as shown in Table 2.

It was found that the constant users were much more likely to demonstrate "positive" circumscribed thinking (59%, compared with 41% for non-constant users), and fewer were driven solely by requirements (21% compared with 31%). Constant users also showed less evidence of "negative" circumscribed thinking. The interpretation of this result is subject to the problem of causation. From these data, we cannot say definitively whether the constant CAD use has tended to skew the behaviour away from negative circumscribed thinking and towards positive circumscribed thinking, or whether people who are already predisposed to this characteristic are more likely to go for the jobs that involve constant CAD use.

With regards to bounded ideation, it was hypothesised that constantly sitting in front of a CAD workstation throughout the working day might not be the most conducive environment for creative thinking, and that this would be evident in higher levels of bounded ideation. This turned out to not be the case. The constant users showed a higher response rate (up from 26% to 36%) for Response 1, which indicated that bounded ideation was not a problem, and a lower result for Response 3, which indicates moderate levels of bounded ideation. This would seem to disagree with the hypothesis, and suggest that constant CAD use may not be a barrier to creative thinking at all, and that it may actually enhance it. However, the difficulty with this conclusion is that the direction of causality is again unclear. For instance, an alternative interpretation could be that the designers who have an existing affinity for CAD work are both less likely to report problems with bounded ideation, and are drawn into the jobs that involve constant CAD use.

Both of the premature fixation questions showed differences between the constant and non-constant users. In general, we can say that constant users seem to be biased towards creating the conditions that could lead to premature fixation, and are also more likely to show evidence of the phenomenon. Their responses were higher for both the "Immediate implementation, highly structured" response to the first question, and the premature fixation response to the second question.

Table 1
Effect of level of experience

	Response rate	
	Inexperienced (3 years or less)	Experienced (more than 3 years)
Circumscribed thinking		
Response 1 ("positive" circumscribed thinking)	58%	51%
Response 2 (driven by requirements)	19%	26%
Bounded ideation		
Response 1 (no evidence of bounded ideation)	44%	30%
Response 2 (evidence of slight bounded ideation)	36%	50%
Premature fixation question 1		
Immediate implementation, unstructured model	21%	27%
Delayed implementation, unstructured model	4%	10%

Table 2
Effect of level of CAD usage

	Response rate	
	Constant users	Not constant users
Circumscribed thinking		
Response 1 ("positive" circumscribed thinking)	59%	41%
Response 2 (driven by requirements)	21%	31%
Bounded ideation		
Response 1 (no evidence of bounded ideation)	36%	26%
Response 3 (evidence of moderate bounded ideation)	8%	20%
Premature fixation question 1		
Immediate implementation, highly structured model	16%	9%
Delayed implementation, highly structured model	41%	51%
Premature fixation question 2		
Evidence of premature fixation	7%	1%

5. Discussion

These results illustrate some of the positive and negative ways in which CAD influences the creative problem solving process in engineering design. It is clear that the strengths of the current, most widely used 3D mechanical CAD programs lie more at the detailed stage of design than the conceptual stage. When CAD is used early on in the design process, it is often used in an unstructured way, with the aim of trialling and visualising alternative ideas, and is usually supplemented with other creative processes such as sketching and discussing ideas in groups. We can speculate that when it is *not* used in this way, the creative potential of the user may suffer. Two groups of users – those who are inexperienced and those who use CAD constantly – seem to be particularly susceptible.

The creative design process may also be detrimentally affected when the designers over-reach the design task and become enamoured with the elaborate functionality of their CAD tool. Again, those who are inexperienced and those who use CAD constantly are more prone. On the other hand, constant users are *less* prone to being affected by either the limitations of the CAD tool or the limitations of their proficiency with the programme. Inexperienced and constant users are also less likely to find that low levels of motivation are affecting their creative abilities. It is still an open question as to why inexperienced users and constant users behave in such similar ways, and this issue may be the subject of further research.

The results of this study have important implications for both users and developers of CAD tools, with regards to promoting creative problem solving and avoiding potential barriers.

5.1. Suggestions for CAD users

Based on the findings of this study, some practical suggestions for CAD users can be made. Firstly, CAD users should not forget that CAD is not necessarily the best medium for the creative, conceptual aspect of design — some consider it to be a documentation tool rather than a true "design" tool. Industrial designers and architects are particularly aware of the importance of designing and communicating through sketches and discussions with colleagues, especially in the early, conceptual stages [25].

Creative people are able to draw on a wide range of ideas and experiences and apply them in unexpected ways [26], and work colleagues can be an important source of these ideas and experiences [27]. There is a danger that when CAD is used "constantly", these interactions are avoided. Constant users should also remember that it is usually best to be driven by the requirements of the task — aiming for "perfection" can have its drawbacks. Experienced users, on the other hand, should be aware that low motivation can affect their creativity [18]. However, most experienced designers seem to be implicitly aware of the embedded "trap" contained in the functionality of modern, parametric tools which sometimes encourage us to build too much structure into our CAD models too early.

Reflecting on this advice, the question arises of whether a computer can ever be an appropriate medium for creative work. An extreme view is that taken by Mitchell [11]: "Because creativity is associated with novelty, comprehensive [computer] tools for creative work will be neither possible nor necessary to develop, any more than it is necessary for a pencil to include all functions for drawing". However, the evidence suggests that there is no reason why CAD cannot be an effective partner to engineering designers in their conceptual work, as long as both the users and developers of CAD tools aware of the potential pitfalls.

5.2. Implications for CAD developers

CAD developers must either change their approach to supporting conceptual design, or acknowledge that CAD is simply not the best medium for this kind of activity. As noted by Burleson and Selker [28], today's tools often contain interface elements that stymie creative efforts. User manuals, tutorials, training courses, and popup "tips" are perhaps appropriate places to make users aware that good design practices do not always involving sitting in front of a computer. Conceptual and detailed design are two very different kinds of activities with sometimes conflicting requirements [29,30]. Software is better suited to supporting detailed design, which tends to be a more structured activity. Creativity, on the other hand, is often seen as being hampered by an overly structured approach [31].

Nevertheless, there are some simple strategies for creativity support that CAD developers may wish to consider. One approach is to promote interactivity, both within teams (via "groupware" [27]) and among the wider CAD community. These communities could encourage the generation of creative ideas by providing access to alternative solutions to similar problems, and could promote both "best practice" and "most unusual practice". Being able to modify and re-use the ideas of others is a key enabler of innovation [32]. Another approach might be to make the design criteria for each part or design task both highly visible and easily modifiable [30]. It has been suggested that creative thinking is essentially about modifying constraints [33].

Developers should also be aware that "feature creep" in CAD functionality may have a negative affect, if users are distracted from their core task by elaborate new features and busy interfaces. Finally, flexibility is a key enabling factor for creativity, and an over-emphasis on parameterisation and structure may make small design changes easier for the user, but it also reduces their flexibility to make significant changes.

The scope of this study did not extend to cover the use of more recent tools specifically intended for conceptual design. The focus was on those tools which are currently extensively used in practice. Recently, add-ons to the leading CAD programs, as well as specialised tools for conceptual design such as Sketchup and Spaceclaim, appear to be addressing some of the deficiencies evident when using CAD for conceptual design. The developer's descriptions of the tools frequently emphasize "flexibility", which may reduce the effect of premature fixation, "powerful features", which could partially address the issue of circumscribed thinking, and in some cases, even playfulness and "fun" which we can speculate may help to encourage creative thinking and address concerns about bounded ideation. It is impossible to assess whether these encouraging signs address the problems identified in this paper without a study of the use of these tools in practice. Such an investigation lies beyond the scope of this study, but would be an interesting subject of future research. Nevertheless we can say that the fact that such tools have been developed is further evidence that there are problems with the most prevalent CAD tools.

5.3. Applicability for findings

The case study investigation involved the collection of rich, detailed descriptions of design practice. However, as it was conducted from the perspective of one project, it did not allow for the findings to be generalised beyond that project. The survey confirmed that the most of the phenomena observed in the case study were not isolated to that one specific instance, but have relevance in the wider CAD community. The four phenomena clearly resonated with many (but not all) of those who responded to the survey.

The analysis of the survey did uncover several findings that were not expected. This is evidence that the potential problems of "leading" the respondents and of predetermining the results were largely avoided. There was sufficient scope for disagreement and for uncovering surprises.

One possible limitation of the survey is the potential for "selection bias" to occur. The type of people who responded to the survey may have been predisposed towards answering in a particular way, and this had the potential to skew the results. To mitigate these effects, a large amount of data was collected on the background of the participants, so that where biases did exist, they could be identified and noted. Ultimately, though, this was essentially an exploratory study, and the aims were to gain a better understanding of the issues involved and provide some assistance to practitioners and CAD designers.

6. Conclusions

An embedded case study identified four phenomena that characterise the impact of CAD tools on creative problem solving in engineering design. They were: enhanced visualisation and communication, premature fixation, circumscribed thinking and bounded ideation. An extensive online survey of CAD users confirmed that the first three phenomena are quite widespread in engineering design practice. On the other hand, bounded ideation occurs relatively infrequently. Users who are inexperienced and those who use CAD constantly tend to be more affect by circumscribed thinking and premature fixation, and less affected by bounded ideation.

The research sheds light on current CAD practice, and the nature and importance of creativity in engineering design. The results provide a basis for advising the developers of CAD tools on ways to enhance systems for use during the conceptual phase of product development. They also provide useful advice for designers in how to foster creativity and how to avoid possible pitfalls in the use of CAD tools.

Appendix

12. Recall situations in which you have had to *communicate* a design which is immature or NOT FULLY DEVELOPED to colleagues. What medium do you tend to use?

	Very often	Often	Occasionally	Rarely	Never
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					

13. Recall situations in which you have had to *communicate* a design which is mature or FULLY DEVELOPED. What medium do you tend to use?

	Very often	Often	Occasionally	Rarely	Never
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					

14. Recall situations in which you have had to *visualise* (for your own purposes) a design concept which is immature or NOT FULLY DEVELOPED. What medium do you tend to use?

	Very often	Often	Occasionally	Rarely	Never
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					

15. Recall situations in which you have had to *visualise* (for your own purposes) a design which is mature or FULLY DEVELOPED. What medium do you tend to use?

	Very often	Often	Occasionally	Rarely	Never
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	○	○	○	○	○

16. Which of the following best describes your work as a CAD designer:

○ I love the power of my CAD tool provides me with. Often, I go beyond merely satisfying the requirements given to me, aiming for "perfection". I would not be able to do that if I was not such a proficient user of such a powerful tool.

○ The details of my designs are always driven by the requirements. The final design would be the same no matter what design tools (computer or otherwise) I was using, although using some tools would take longer than others.

○ The details of my designs are mostly driven by the requirements. Sometimes I find that the CAD tool I am using affects the results, because some functions are easier to perform than others. If I were an expert user using a perfect tool, it would be slightly different.

○ Some of the "features" of my designs are actually by-products of the tool I am using. Sometimes these features negatively affect the performance of the final product. I try to avoid it as much as possible, but it happens.

○ Often I cannot achieve what I want to achieve with my designs because of limitations of the CAD tool I am using, of because I am better at other methods of designing.

○ I cannot relate to any of the above descriptions (please explain)

17. Which of the following best describes your motivational state when using CAD:

○ I love using CAD. Being able to generate something new out of nothing fills me with creative energy, and seeing it taking shape on the screen is exciting. I love the sense of awe I can create in other people when they see a complicated model I have created.

○ I enjoy creating designs using CAD and I enjoy showing my models to other people. Sometimes doing the details can be a drag, particularly late in the design stage, but I don't mind.

○ My CAD work if fairly evenly divided between interesting enjoyable tasks on the one hand and boring and frustrating tasks on the other. There are good days and bad days.

○ It's a job. Sometimes I get inspired if I have an interesting task to work on, but mostly its a bit of a drag. I get frustrated and annoyed doing repetitive tasks or when the CAD program doesn't do what its supposed to do.

○ CAD sucks my will to live. I thought designing would be creative, but sitting in front of a computer all day doing endless details and having to constantly deal with software bugs is just mind-numbing. A trained monkey could do my job.

○ I cannot relate to any of the above descriptions (please explain).

18. Imagine you are involved in a design task that is a small part of a larger project. The task is to develop a hatch that must automatically and reliably close to stop high pressure gas escaping from a pressure chamber. In the early stages of design, you come across a problem. What type of mechanism will you use to close the hatch? In a design meeting with your colleagues, the suggestion is made to go with an electric motor. It's probably not the only option, but it sounds like a decent idea. You can't see anything immediately wrong with it. Your design manager tells you to "see how it goes".

○ You return to your CAD workstation, considering the best way to proceed. What do you do next? (If possible, try to recall similar incidents from your own experience, and recall what you actually did.)

○ (*Immediate implementation, highly structured model*). First, you work out the structure the files should have. You plan for a high level of parameterisation of the CAD models and interconnection between the various files. Your know that this may not be the "final" design, so if things change, you want to be able to make a few parameter changes in a critical place and have all of the associated changes happen automatically. This should make things easier down the track.

○ (*Delayed implementation, highly structured model*). You decide to take a minimalist approach for now, and implement only a basic conceptual model of the motor and associated mechanism. You know that this may not be the "final" design, so if things change, you don't want to have to start again from scratch. Eventually, you want to have a high level of parameterisation of the CAD models and interconnection between the various files, but to implement then too early can be more of a hindrance than a help.

○ (*Immediate implementation, unstructured model*). It was a decent idea, and this design concept deserves to be implemented and detailed quickly, even if only on a trial basis. You know this may not be the "final" design, but you would prefer to get things moving with what you have at the moment. Parameterisation of the CAD models and interconnection between the various files is not important, particularly at this stage. It is often more trouble than it is worth.

○ (*Delayed implementation, unstructured model*). You are hesitant. You have been burnt in the past by committing to certain proposed concepts too early and you don't want to make that mistake again. You would prefer to let the concept mature by drawing some sketches and discussing the idea with colleagues, before committing time and effort which could well be wasted. You don't believe in building highly structured models as this wastes time and can cause unexpected problems later on.

○ Other (please specify).

19. Let's assume you chose the first option — that is, you immediately implemented a highly structured, parameterised model. You have chosen the necessary off-the-shelf components and have the preliminary design of the electric motor and associated mechanism. A few weeks later, you have a design meeting, and somebody proposes a different design concept — instead of an electric motor you could tap into the existing pneumatic system, using a pneumatic cylinder to drive the door closed. It's a surprising idea that nobody else had thought of, and it has several merits. The final design would be simpler and there would be less risk because there would be fewer modes of failure. It would be up to you to implement it. By now, you have invested considerable time and effort into the original concept, using electromechanical components. You have spent time parameterising and interconnecting various parts of the model so that fine tuning would be easier, but all of that would be wasted if the new concept was chosen.

Your design manager asks your opinion (as the designer who would have to implement this new concept). How do you respond?

◦ At the meeting you argue that the new concept be implemented, even though it will mean more work for you. All of the effort that you put into the previous concept would be wasted, but the new concept is obviously a better idea, and is easily worth the extra effort.

◦ You argue strenuously against the change. If you had known earlier that this would happen, you wouldn't have put all that work into the original idea. Besides, a mature and satisfactory concept (which the original concepts has now become) is better than an immature concept that strives for "perfection". Change for the sake of change is pointless.

◦ Other (please specify)

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