Design Engineering for Universal Access: Software and Cognitive Challenges in Computer Based Problem-Solving

Gisela Susanne Bahr(✉), Stephen Wood, and John William Blood

Florida Institute of Technology, 150 W. University Blvd, Melbourne, FL 32901, USA
{gbahr,swood}@fit.edu, jblood2012@gmail.com

Abstract. Computer-supported problem solving has become ubiquitous in work and home environments. Within an educational context, specifically design engineering, this paper investigates a framework that integrates two aspects of these interactions that influence the outcome of computer based problem solving: software and mind-set involved in the interaction. The review indicates a number of research opportunities for interaction science to enhance problems-solving and is focused primarily on software tools and solutions that enhance cognitive performance for specialized user populations.

Keywords: Access to education and learning · Adaptive and augmented interaction · Design for all education and training · Interaction science for universal access

1 Introduction

Computer-supported problem solving, frequently online, has become an everyday task. This phenomenon is the result of increasingly migrating everyday problem solving tasks involving interactions with people and real-life materials [1] to computer supported contexts. This trend has been observable in Western society among many domains, including education, and particularly in *design engineering*. The challenges that have arisen for this specialized user population in computer supported problem solving, are relevant for universal access as the scope of computer use related to problem solving increases.

The practitioners and students in the discipline of design engineering are considered highly creative individuals who invent novel solution to ill-defined, non-routine problems [2, 3]. The problems they solve are unstructured and ill-defined and require the use of inferences, coordination of information, with leaps of intuition and creativity. The primary tool in this field is the use of computer aided design (CAD) software. This paper reviews and describes cognitive and creative interaction challenges associated with CAD supported problems solving and identifies opportunities for interaction science to enhance cognitive performance of specialized user populations. These interaction challenges are related to universal access issues with focus on open-ended problem solving. This paper reviews research on CAD and problem

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solving, the effect of software properties on creativity in problem solving, relevant prior research in cognitive psychology, and the implications and challenges for interaction design to support non-routine problem solving.

2 CAD and Problem Solving

CAD software was initially developed for the drafts(wo)man to convert the hand drawings of the design engineer into digital drawings that could be saved on the computer. The software was later adapted so that the design engineer could enter his or her drawings directly into the computer without waiting for the drafts(wo)man to do so. In the process more capabilities were added to CAD software to aid the designer. The evolution of CAD began with 2D, then 3D, computerized drawing tools that led to parametric CAD solutions. Parametric approaches change parameters and automatically update corresponding elements.

Over the years, design engineers have come to rely on CAD software for the entire design cycle from conceptual development to layout design to final concept design, and production. However, CAD was initially not intended for the "creative" phases of product design, nor to support divergent thinking during concept development.

The notion of treating product development and innovation as a non-routine and creative problem solving task is well established in research and practice [4]. As a result, software supported problem solving has been investigated in the areas of engineering and architectural computing [5]. In this context, computing supports the entire process from idea generation to transferable solution. During this process, it appears that creativity is instrumental during the early stages of design [6], which include concept development and the investigation of the problem space.

Problem solving using CAD in engineering contexts provides opportunities as well as challenges. For example, [7] suggest that the use of CAD tools promise more rapid and inexpensive problem-solving because of the use of simulation and that this practice is likely to create possibilities for learning and design innovation. Similarly, [8] support the idea that virtualization of knowledge-based processes is likely to result in new solutions.

An empirical study how CAD applications affect the problem solving process is Fixson and Marion [9] 2012 investigation of CAD use in product development. The study evaluated the whether the advantages attributed to the use of parametric CAD software are grounded in fact. For example, CAD use supports design iteration, testing and faster transmission of the design, compared to previous practices during product development. Moreover, it is generally accepted that CAD enhances product development through wider exploration of the solution space and by requiring faster and less development resources. The cost savings are accomplished through the use of computer-based simulation, early in the design process (front-loading). This practice is expected to reduce the need for prototyping, which tends to be costly and occurs during the later stages of product development.

The investigation confirmed that the availability of CAD systems tends to reduce prototyping costs but it also revealed that CAD availability does not accelerate product development but reduces concept development by facilitating detail design too early in the process. Moreover, the ease of making changes has the potential to erode process discipline and can lead to last minute changes. They refer to these CAD effects on problem solving as back-loading, in contrast to the front-loading, i.e. simulation early in the development.

The authors conclude that *"[The] side effects of digital design come from its major strength, the ability to iterate detailed models. This study illustrates that the different thinking modes that underlie divergent and convergent phases in product development as well as process discipline effects need to be considered when applying the idea of front-loading via extensive use of digital design tools such as CAD…In short, front-loading the downstream process should not result in a quasi back-loading of concept development work into the detailed design phase; the different thinking modes that are appropriate for each phase make this merger counterproductive. Nor should a quasi back-loading occur due to pushing detailed design issues into the tooling phase just because it is possible."* [p.154].

In summary, the nature of interaction support in online problem solving, here during CAD interactions, is a driver of problem solving cognition and leads to changes in the process as well as outcomes. It appears that the medium or tools used during the design are capable to fundamentally guide and shape the underlying cognition. CAD in particular was not originally designed to support concept development and the divergent thinking phases of design. Moreover it appears that one of the key properties that enables the front-loading and back-loading phenomena is parametric design, the ability to make changes relatively easily that automatically propagate and update the design.

3 CAD Software Properties and Their Effects on Creativity in Problem Solving

Parametric approaches change parameters and automatically update corresponding elements. Hence designs can be adjusted and tweaked easily and likewise new solutions can be derived from prior solutions with relative ease. As such the capabilities of the interfaces not only influence the interaction, but may also influence the generation and type of problem solutions.

Research on engineering design creativity has explored the relationships of cognitive styles, creative quality and quantity of solutions. For example, [10] investigated the relationship between cognitive styles and problem solution quality and quantity. The measurements and comparisons of the participants based on their cognitive style using the Kirton Adaption-Innovation Inventory (KAI) were nonsignificant. The KAI is a psychometric instrument intended to measure cognitive style along a continuum, from adaptive to innovative. This measure was not correlated to the generation of derivative versus novel solutions when comparing engineers to a control group.

However, the researchers observed that problem solvers who base their design on previous solutions generate more solutions than problem solver who invent and create novel, non-derivative approaches. They base this observation on paper design and prototypes build from a fixed set of material (each set included 1 plastic bag, 8 rubber bands, 8 pipe cleaners, 8 Popsicle sticks, a 4″ × 8″ piece of foam core, a 4″ × 12″ flat foam sheet, and 12″ of tape). (For a review of alternative creativity measures see [11].

One might argue that using an initial design as a basis for additional deigns is systematic as well as the result of the limitations of the medium. The question arises whether the addition of drafting technology capabilities facilitates creativity and innovation?

Chang [12] investigated student cognitive abilities and problem solution performance on design engineering tasks using 3-D CAD compared to a control group. They found that measures of spatial ability were moderately correlated with creative performance, i.e., spatial ability accounted for 6–12 % of the variance. In addition, results indicate a difference between students in the CAD user group and the drafting control group, suggesting enhanced creative performance primarily relating to aesthetics, in the CAD condition. While these finds are encouraging, it is noteworthy that the apparent effects of 3D-CAD use are confounded with the instruction technique used for the 3D-CAD user group and the traditional design group.

For example, the traditional design group received (1) General introduction to graphic design and graphic recognition (2) Types of graphics (3) Introduction to common graphics tools (4) Presentation of object shapes: isometric plan, oblique drawing, perspective drawing and orthographic view. On the other hand, the 3D-CAD user group was instructed in (1) Purpose and types of 3D-CAD software (2) Thinking corresponding to the visual basis and digital operation (3) Reverse thinking pattern for modeling (4) CAD basic exercises and comprehensive application: basic geometric style, basic geometric style change, construction of concave surface of contour lines and comprehensive application of commands. Given the difference in the instruction, it is not clear whether the observed differences are the result of different conditions (drafting tool), or the instruction, or both.

To examine the potential impact of CAD tools on creative problem solving, [13] conducted an on-line survey with 212 experienced users on the ways that CAD use may influence their ability to design creatively. Results suggest that for immature designs (concept development), CAD use was not preferred and that experienced designers preferred free hand sketching, drawing boards and verbal discussions. Some survey respondent pointed out that they over-used CAD and that this appeared to restrict their spontaneous thought and expression. Another possible influence of CAD use is related to circumscribed thinking. Ideally a design engineer is motivated to find a solution based on the requirements given. Circumscribed thinking occurs when the capabilities of the tool or the designer's proficiency of the tool use affect the solution. The results indicate that circumscribed thinking that shapes the solution (instead of or in addition to the requirements), is a wide spread issue. Respondents attributed negative as well as positive outcomes to the phenomenon. Another aspect investigated was the phenomenon of premature fixation. Self-reports indicate that full use of CAD early in the design is more likely to be associated with premature fixation. It appears that designers deliberately downgrade CAD capabilities and use CAD as a simple drafting tool for computer based sketching and that they thereby avoid CAD's parametric and 3D capabilities.

It appears that CAD is less useful during concept development, leads to solution fixation if used during concept development and facilitates circumscribed thinking.

In light of these findings, the conclusions put forth by the investigators are (1) the use of smart interfaces that actively support creative thinking and practices of the user and (2) the control of feature creep, which is the distraction of the user from the core tasks by elaborate new features and busy interfaces. Clearly, problem-solving enhanced CAD environments must strike a balance not to disrupt and yet facilitate the creative process of the design engineer. The next section highlights relevant research in cognitive psychology that is related to building CAD environments that support non-routine problem solving.

4 Related Prior Research in Cognitive Psychology

In 1972 in their seminal book on the theory of human problem solving, Newel & Simon's laid the foundation for conceptualization human problem solving as the search of the problem space [14]. Because problem spaces of non-routine problems can be quite large, corresponding searches are guided by heuristics or rules of thumb in order to select from a large number of options without conducting exhaustive and time consuming comparisons. The use of heuristics or some form of prior knowledge and preferences during non-routine problem solving tasks, does not address unpredictable "leaps of intuition" and insights that occur during solution search. The seminal work in the domain of insight in problem solving was conducted by Koehler in 1910s who investigated apes who apparently demonstrated insight in problem solving situations [15]. One of the primary observations of this and later studies with humans was that while thinking about a problem, problem solvers can "restructure" their representations of the problem. This change in the representation can lead to a flash of insight that enables problem solvers to invent a novel solution.

Kaplan and Simon [16] investigated insight in the mutilated chessboard problem and found that different visualization of the problem representation had an effect on the occurrence on insight. (See for [17, 18] an overview of the mutilated chessboard problem.) The mutilated chessboard is a tiling problem, where two diagonally opposite tiles have been removed from the board and the task is to cover the remaining 62 tiles or squares with 31 dominos that cover 2 squares at a time. The task is impossible. Kaplan and Simon's investigation suggests that problem solvers who attempted to search the problem space by simulating the solution had difficulty remembering and keeping track of their solutions. On the other hand, problem solvers who recognized that each domino must cover two differently colored squares realized that it would be impossible to cover the board because two squares with the same color had been removed. This insight to the impossibility was greater when the two colors the chessboard squares were labeled bread and butter, respectively.

The approach of restructuring a solution to inspire insight is related to the notion of mind-set and functional fixedness. An example how mindset or frame of mind can prevent reaching a simple, uncomplicated solution is this riddle: A man visited the pyramids in 1993. The trip moved him deeply and he promised himself that if he ever had children to bring them to see the pyramids. Finally, in 1978 he took his very own son to see the sights. How was this possible? (The answer is provided at the end of this paper.)

The riddle may seem unrelated to problem solving in engineering at first but it illustrates the influence of mindset and assumptions (Einstellung) on problem solving. A recent example are the terrorist attacks that occurred on September 11, 2001 in metropolitan areas of the USA [19, 20]. Four planes (commercial jets, which are generally considered means of transport for goods and people) were used as weapons and killed thousands of people. The realization is that the function of a plane is not limited to preconceived notions, such transportation, but that the possible uses of an object depend on the characteristics of the object. While unintuitive, it was obvious to the terrorists that planes could serve as airborne, target finding bombs. Appearances, whether they take the form of a problem context or the current usage of an object, lead problem solvers to adopt a particular mindset (Einstellung) [21]. This finding is not surprising except that the consequences extend beyond the laboratory, as seen in the 9–11 example. Moreover, functional fixedness and Einstellung are considerable obstacles to seeing alternative solutions. Based on prior research it appears that restructuring of a problem representation can alleviate these phenomena and lead to insights that reveal a solution. The implications of this work in context with CAD are the topic of the next and last section.

5 Challenges for Interaction Design to Support Non-routine Problem Solving

Despite the belief that sophisticated CAD solutions support creative processes, there appears to be some evidence from surveys with experienced engineers as well as from studies with junior/novice engineers that this idea requires investigation. Several challenges for using CAD as a non-routine problem solving environment have emerged during this review.

- CAD was not designed for divergent thinking but detail design.
- CAD use during product development undermines concept development.
- CAD use early in the design process is associated with premature solution fixation, circumscribed thinking and feeling cognitively restricted.

Given the limitation and impact of CAD when used early in the design cycle or product development, it appears that a framework is required that integrates the demands on cognitive processing with the workflow and the capabilities of the interaction tool. Hence, a solution implies the flow of continuous interfaces with different capabilities that appropriately support the underlying thought processes such as divergent and convergent thinking. Rather than relying on one CAD environment to support a multiplicity of tasks and encumbering the user with inappropriate features, a cognitively friendly CAD environment that support problem solving consists of a suite of continuous interfaces that easily transition between the support for idea generation, concept development to layout design and details design. In particular during the creative phases, such as idea generation and concept development, alternative interfaces should supply tools for hand drawing, peer communications and easy idea sharing. Such interfaces would be void of the sophisticated drafting tools because at this state in the development they are irrelevant and potentially commit the user prematurely to a solution.

The availability of creative CAD support tools does not guarantee their use. In particular, under time pressure any workable solution is deemed acceptable, whether innovative or not. The reality of time as a limited resources, adds a considerable constraint to design engineering that can impact and abbreviate concept development regardless of the tools used. It remains to be shown how the concept development can be accelerated with cognitive support tools that alleviate possible negative impacts of time pressure and alleviate solution faction and derivative design. For example, when time is of the essence, solution fixation is likely to arise to step up progress on the project. However, it is important to consider alternative solution to prevent expensive back-tracking or back-loading resulting from solution fixation. A smart CAD support tool may supply alternative solutions when designer fail to adopt divergent thinking styles. Hence divergent thinking or exploration of the solution space can be actively prompted by the interface.

Related existing CAD solutions are “design advisors,” that serve an error checking function by searching for design violations [22, 23]. For example, a sheet-metal design advisor will prompt the CAD user if a hole is too close to an edge, which is a point of failure, i.e., a weak or breaking point. Similarly, a plastic injection molding design advisor may alert the user to choose correct angular settings so that the mold will be able to release the plastic part. [24] More sophisticated types of advisors could involve restructuring of problem representations by suggesting alternative solution components.

An example is the design of the bottom of a wave tank (see Fig. 1). A wave tank contains thousands of gallons of water and is used to simulate ocean waves and to measure the effects of objects in the wave flow. The shape of the bottom of tank (bottom bathymetry) is critical to the realistic simulation of the ocean floor. An open-ended design problem is how to create an adjustable system to shape the tank bottom as needed with specific parameters. A number of ways are possible. For instance, one might empty the tank and cover the bottom with a new, specifically molded surface each time changes in the simulation environment are necessary. Similarly, one might conceive of a scuba diver to reshape the bottom by adding, removing or adjusting devices. On the other hand, a design engineer may be tasked to design an automated solution to make tank bottom bathymetry adjustable. Typical approaches to such a system could utilize a flexible bottom that is raised by electric pistons or hydraulic cylinders. Another functionally related, albeit less obvious solution is the use of a cam system. Camshafts are generally found in automobile engines (see Fig. 2). A camshaft consists of a series of cams attached to a shaft. Using an individual cam is equivalent to using an individual piston or hydraulic cylinder, where each has a specific location under the wave tank bottom and can raise or lower to contour the bottom. During the concept development of such a system the functional equivalence can be presented by the CAD system in order to expand the solution space with concepts from automotive engineering. Presenting multiple possibilities to the designer during concept development has the potential to alleviate solution fixation by changing mind-set and the mental model of the problem representation, and by creating association to other domains. The effect is likely to occur regardless of time pressure because it relieves the cognitive workload associated with idea generation and compensates for a lack of knowledge and stimulates divergent thinking.

Fig. 1. Ohmsett Wave Tank in Leonardo, New Jersey, USA. [25]

Fig. 2. Image of automobile camshaft. (Camshaft rotates to actuate pistons, not depicted.) [26].

It is easy to see that enhanced CAD interfaces that support problem solving must strike a balance not to disrupt and yet facilitate the creative process of the design engineer. This implies the use of multiple interfaces that are designed to support different cognitive processes as well as advisors that suggest functionally related solution to prevent solution fixation under time pressure or because of conventional CAD overuse. Likewise problem solving in universal access requires awareness of the underlying cognitive demands on the user and appropriate interface design. The notion of one size fits all, i.e., one interface fits all cognitive processes underlying problem solving, has been questioned in CAD research and has implications for problem solving support beyond design engineering communities. Future research is likely to illuminate the complexity involving computer supported problem solving in everyday life, such as planning your vacation on a budget or organizing a funeral in a short amount of time. The universal accessibility to computers for problem solving creates challenges not only as the result of disabilities but also because of the cognitive needs and demands of the task to be accomplished. Hence the notion of universal access is inclusive not only of enabling access to information technology, but also of finding ways to cognitively assist the users of information to solve problems in a meaningful and productive way with computer support.

6 Riddle Solution

The man made his trip in 1993 *BC* and took his son 15 year later on his second trip in 1978 *BC*.

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