Design Engineering and Human Computer Interaction: Function Oriented Problem Solving in CAD Applications

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Abstract. CAD Software such as CREO and SolidWorks are used to develop mechanical parts and assemblies and do not explicitly support the function of the feature, component, part or assembly. Therefore, the reasoning of why and how a design is developed has not been incorporated into current CAD systems. At the same time, CAD systems support sophisticated functions such automated routing, modelling and simulation of dynamic and geometric properties and design solutions tracking. In this paper we investigate (a) to what degree CAD tools have advanced beyond drafting tools to include cognitive supports that facilitate problem solving and (b) which possibilities exist to enhance CAD with cognitive tools that with focus on the intersection between cognitive psychology, interaction design and design engineering remain unexplored.

Keywords: Engineering design · Design reasoning · Design support · Design cognition · Problem solving · Creo · SolidWorks · Functional fixedness

1 Introduction

Design engineers rarely have the opportunity to use algorithmic approaches, but solve ill-defined problems with creative and novel solutions. For example, the design of an Autonomous Underwater Vehicle (AUV), such as the Bluefin AUV used to look for Malaysian Flight 370 that was lost March 8, 2014, requires thousands of design decisions that are based on (often changing and poorly defined) customer requirements. Mechanical components, electrical circuits, computer code, and all of the connections are interwoven by mechanical, electrical and computer design engineers to create the AUV. It is easy to see from this example that the task of the design engineer is not to reproduce prior solutions but to develop a novel approach and a creative solution to design an innovative, complex vehicle.

When conceptualizing design engineering as a creative problem solving process, the question arises as to the underlying cognition, specifically, how information processing of the design engineer can be supported during the development of solutions. In addition to traditional drawing and sketching, CAD (computer assisted design) software is a primary tool of design engineers to develop and articulate their solutions. CAD tools are sophisticated and popular as computerized drafting tools but questions

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remain unanswered whether CAD applications support the cognitive aspects of problem solving. As early as 1989 [1] observed that CAD tools provide computerized versions of traditional drafting and that these approaches had not yet realized the possibility of supporting the design process beyond the mechanics of drawing. Furthermore, he observed that CAD applications did not support problem solving and solutions finding, specifically in the context of function based thinking, which is instrumental to design engineering. In this paper we investigate (a) to what degree CAD tools have advanced beyond serving as drafting support and include cognitive tools that facilitate problem solving, and (b) which implementation possibilities remains in CAD for cognitive tools that are supported by interdisciplinary research in cognitive psychology, interaction design and design engineering. In addition to this introduction and the conclusion, this paper has four parts. Part 1 is an overview of problem solving including human biases and cognitive artifacts that impede ill-defined problem solving. Part 2 is a review of that state of the CAD software and which tools are provided, including possible cognitive tools. Part 3 integrates the cognitive psychological findings with the state of CAD. Part 4 reviews the seminal study on function based problem solving in the design process and presents research opportunities for enriching CAD application with cognitive tools. We conclude that the state of CAD as cognitive support tool for the design engineer is in its infancy and substantial cognitive research of the design process and software development is still to be done.

2 Review of Cognitive Phenomena in Problem Solving

To answer the question whether CAD tools have advanced to include cognitive tools that facilitate problem solving for engineers, we first present a review of cognitive phenomena that apply to design engineering.

Developing a solution to an engineering task, such as to “build an autonomous underwater vehicle that can do these things” is an instance of solving an ill-defined problem. Unlike well-defined problems, ill-defined problems lack definition, which may be a somewhat elusive goal or uncertainty how to reach a goal, i.e., not knowing which necessary steps and what resources are available [2]. In design engineering the lack of problem definition is expressed by a lack of specific or generic requirements and uncertainty about the tasks that need to be performed to reach the goal. To support the design process and productive thinking [3], strategies such as the House of Quality model have been developed [4]. Such strategies encourage perspective taking and the discovery of dependencies and expectations and tend to be paper or whiteboard based. They are primarily used as communication tools between customers and the engineering team and aide in defining the goals of the project but are less useful and not intended to support creative problem solving during the design process.

2.1 Functional Fixedness

A well-studied phenomenon that occurs during ill-defined problem solving is a fixation of the typical use of an object. For example, a hammer is made for hammering, a toothbrush for cleaning teeth, etc. Karl Duncker discovered the phenomenon that people tend to limit the uses of previously encountered objects in 1945 and termed his observation Functional Fixedness [5].

The research may seem dated but the phenomenon of functional fixedness persists as an artifact of human information processing. Examples in recent history are the terrorist attacks that occurred on September 11, 2001 in metropolitan areas of the USA [6, 7]. 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 that the function of a plane is not limited to preconceived notions but that its uses depends on the characteristics of the object, was obvious to the terrorist who used the planes as airborne, target finding bombs.

Duncker's original study investigated functional fixedness using ill-defined problems that required productive as opposed to *re*productive, or algorithmic thinking [3]. For example, he invented the candle-wall problem, which is now well known inside and outside of cognitive psychology. The problem description follows: Seated at a table facing the wall, the participant is given a candle, a box of matches, a box of tacks and a task: attach the candle to the wall so that it can be lighted and burn without dripping wax.

This goal is clearly stated but how to reach it is unclear. The results of the study indicate that participants, unless they are already familiar with the solution, tend to struggle. However, when the matches and/or the tacks are on the table, rather than contained in the box, the solution becomes obvious [5]: The box can be used as a candle sconce that is fixed to the wall using the tacks. The critical observation of the research is that problem solvers implicitly place limits on the functions of an object that are related to its current use, context and prior knowledge. This is related to schema use in cognition where a previously learnt framework guides recall based on a set of cues [8, 9]. In this context cues are the current function or usage of an object which appears to inhibit the exploration of alternative uses, i.e., functions or functionalities. By making alternative uses of the object more obvious, i.e., taking the tacks out of the box, problem solvers are more likely to find solutions.

2.2 Analogical Problem Solving

Research related to the obstacles of ill-defined problem that require productive thinking have been also investigated in analogical problem solving. Analogical problem solving refers to the transfer of a solution from one problem to another problem that seems initially unrelated.

For example, [10] presented participants with a fictitious military problem. The problem description follows: The only way to reach a fortress is by road. Many roads radiate out from the fortress and each road is mined so that only a small number of people can traverse them safely. A general is tasked to capture the fortress and plans launch a full attack. Consequently, the number of people needed to take the fortress exceeds the number of people who can safely traverse the roads. The solution to the problem is based on a convergence strategy: Divide the troops into groups that are small enough to use the roads safely, join forces at the fortress and make the conquest.

After receiving the problem and the solution, participants were given another problem, originally described by Duncker [5]. The problem description follows: A patient is suffering from a malignant tumor but surgery is not an option. A high intensity X-ray could destroy the tumor but at the same time would destroy to the healthy surrounding tissue. A low intensity laser would preserve all tissue including the tumor. Without surgery, is it possible to develop a procedure possible that destroys the tumor without destroying the healthy, surrounding tissues? The solution is to use multiple low power lasers that converge on the site of the tumor.

The results show 10 % of the participants who did not receive any additional information or irrelevant information before the radiation problem, solved it. However, 75 % of the participants who received the radiation problem after studying the military problem and receiving the convergence solution with a hint to apply the solution to the next problem, solved the radiation problem. Without specific hints it appears that participants have difficulty in noticing similarities between problems. Research [11] suggests that failure to recognize the commonalities between the problems is the result of deep vs. surface structure processing [12], where surface refers to appearance and deep refers to an abstraction of structural organization. In the current study, the impression that military strategy and cancer treatment seem unrelated prevents participants to shift their focus from the surface to the common, deep structure of the problems unless explicitly instructed to do so. The failure mechanism is simple: dissimilar domains create different appearances (surface structures) and these differences imply that the problems have nothing in common, hence analogical search is not conducted.

It appears that appearances, whether they take the form of a problem context or the current usage of an object, lead problem solving to adopt a particular mindset (Einstellung) [13]. This finding by itself does not seem surprising except that the consequences extend beyond the laboratory, as seen in the 9–11 example.

2.3 Solution Fixation in Design Engineers

Similar to Einstellung and Functional Fixedness, solution fixation is a common cognitive artifact affecting design engineers from the novice to the expert. Prior research [14, 15] focused on professional mechanical design engineers and found that they became fixated upon preliminary solution ideas and failed to consider alternative design concepts. The phenomenon was seen both at the level of the overall design problem and at the level of each individual sub-problem. In addition, [14, 15] observed that if the designer discovered weaknesses in original design later in the process, they were solved by ‘patching’ the design rather than discarding the idea and developing a new concept. According to [14, p. 15]: “The first idea was almost sacred, and sometimes even highly implausible patches would be applied to make it work.” Similarly, [16] in a study of pre-expert electronics designers observed that individuals rarely generated and modelled alternative solutions but focused upon initial ideas that were iteratively improved until they reached a state that was adequate.

In summary, previous studies indicate the design engineers “patch” and “repair” solution ideas instead of questioning or exploring alternative uses of the parts and assemblies they created. From an information processing perspective this means that design engineers tend to limit the functionality of the design elements to the originally conceived design context. This is an instance of functional fixedness.

The findings that the problem context and the current object usage create cognitive artifacts such as surface structure processing, solution fixation and functional fixedness, are likely to have implications for the presentation and organization of CAD tools and the way they are presented in a graphic user interface. Hence we proceed to the next section which is a review of the state of CAD.

3 Review of CAD: SolidWorks and Creo 3.0

We reviewed current CAD packages that are the most widely used in the engineering community: SolidWorks developed by Dassault Systèmes Solidworks Corporation and CREO developed by Parametric Technology Corporation (PTC). Other CAD applications, such as CATIA, AutoCAD, Inventor and TurboCAD offer comparable functionalities.

3.1 SolidWorks

SolidWorks is self-described as a user-friendly CAD program in that it offers a wide range of real-time support in the form of interactive prompts, automatic button descriptions, and tutorial options. Variations of the SolidWorks software packages offer the user varied levels of design and analysis capabilities. They include standard 2D and 3D design capabilities, design and drawing interference checks, automated cost estimation, and online parts and components library, as well as reverse engineering capabilities and wiring and piping design tools.

Design Library. The SolidWorks design library structure relies on a variety of categorization methods of user solutions. The library is organized in a cascading drop-down format with increasing specificity as presented in Fig. 1.

The design library contains a wide range of basic mechanical and geometric objects that can be modified and built upon. These objects range from very basic washers and screws to fairly complex injection mold bases and assemblies. The library incorporates object and form-based cascading menu structures. Menu options can be categorized into the following groups:

- Specific Objects: Object or assemblies of objects too complex to be generalized in menus. Vendor libraries and SolidWorks add-ons offer a range of additional complex objects. Examples are mold base, valve assembly, fittings, etc.
- General Objects: Objects (physical parts) are categorized generally. Each category has its own more specific parts catalog. The library add-on called toolbox is also organized in this manner. Examples are hardware, sheet metal, knobs.
- Forms: While less common, there are a few library menu options that are organized based off of form. Examples are basic sheet metal forms, embosses, flanges, and ribs.

The library also contains a toolbox that has imported screw standards and sizes for 10 different countries. Also, the user has the option to add a file or object to the parts library. In addition, *Partner Products Online Resources* provide functionalities such as vendor libraries (providing object prototypes), automated analysis of the design geometry for piping routing and circuits, plug-ins for computer aided manufacturing (CAM) and computer numerical control (CNC) machining and sheet-metal designs. Perhaps not surprisingly given the number of option and contributors, the library does not have a search feature.

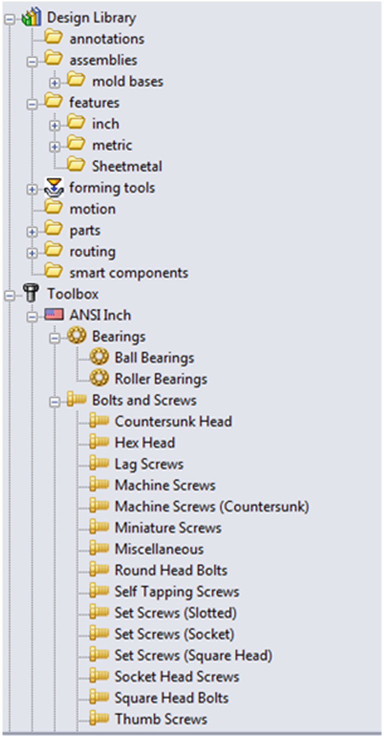

Fig. 1. SolidWorks design library cascade menu [screenshot].

Workflow Enhancements. SolidWorks supports the drafting process with automation, such as auto-sizing and auto-routing tools. For example, if the user drags a generic flange onto an existing fluid tank outlet, the flange automatically sizes and forms into the type of flange necessary to make the proper connection. The auto routing suggests the spatial location where pipes and wires should be positioned and can generate piping layout after an inlet and outlet are specified. An example of "designed by software" is an image of an orthogonally routed solution in Fig. 2.

SolidWorks also provides electrical wire routing tools. For example, the wire auto-bundler can automatically bundle a group of wires and route them through a space given a specified origin and endpoint, fixing the wires to structures for support as needed. Moreover, the auto-routing wire feature can detect ports between components that require wire connections. The software can then automatically add and route the wire connections. In addition, SolidWorks offers software package that is specifically for the design of electrical systems. This software platform is capable of importing electrical schematics and components and converting the layout into 3D space with all the necessary connections.

3.2 Creo 3.0

The Creo design platform is an evolution of the Pro/Engineer software. The software lets the designer "perform analysis, create renderings and animations, and optimize productivity across a full range of other mechanical design tasks, including a check for how well the design conforms to best practices" [17]. Creo has a number of modelling & simulation tools that assist the design engineer. Examples are: Simulate, a structural,

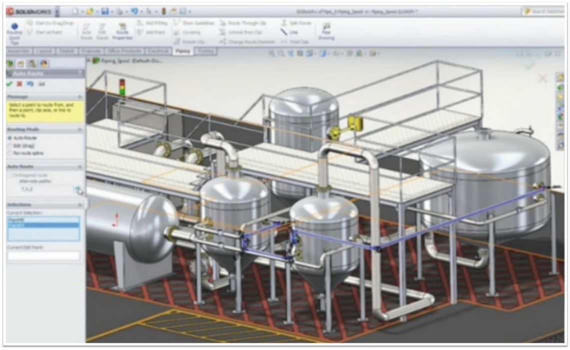

Fig. 2. SolidWorks' auto-route feature [tutorial screenshot]

thermal and vibration analysis tool for the evaluation of 3D virtual prototypes; Mechanism Dynamics, a tool that enables the designer to simulate the forces and accelerations in systems with moving components; Manikin Extension, a tool to test designs against a number of quantitative human factors, workplace standards and guidelines. Similar to SolidWorks, Creo 3.0 offers piping and cabling automation. Other aides include a Tolerance Analysis Extension that analyzes geometric tolerances to verify that components fit together correctly (Fig. 3).

CREO also has import/export compatibility with around 30 common CAD platforms. CREO lacks internal tutorials but has a link to an online tutorial website. Some of the content on the tutorial website is "how to" organized. For example, the home page on the tutorial website contains instructional videos on how to: control tangency, move and rotate, manage chamfers etc. In summary, CREO does not contain a built-in design library and is compatible with wide range of CAD software programs, allowing for access to many external libraries.

Design Libraries. The vendor libraries are extensive and are accessed on a broad object-basis. For example, Creo links to a 3D model database of over 750,000 basic CAD designs available for purchase http://www.3dmodelspace.com/ptc. Models are searchable based on a two-tier menu of objects. Specifically, the 3D Model Space database is hierarchically structured, from broad to narrow. Some of the sub-categories within the menus are organized by type that can suggest the primary function of the object. For example the selection, "mechanical components > springs" gives the user the option of choosing from "compression spring, tension spring, and torsional spring".

Workflow Enhancements. CREO Design Exploration Extension (DEX) saves critical design mile stones to create design branches so the designer can move back and forth between design alternatives; It is based on a design tree structure that allows for alterations to a design while storing the original design files separately. The feature variation is not automated and each version or change to the design needs to be created by the design engineers. A related product, the Advanced Assembly Extension allows critical design information to be shared with individual team members enabling them to complete their tasks concurrently while working within the context of the full assembly.

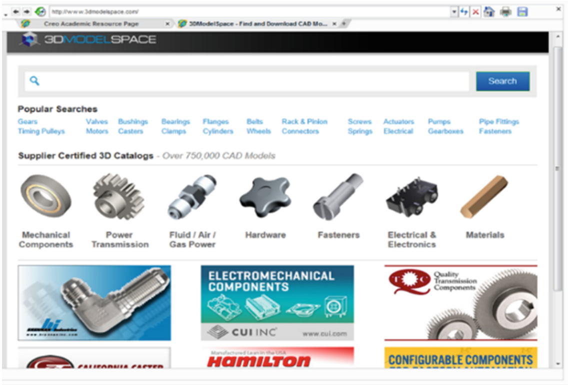

Fig. 3. Online vendor library [3DModelSpace screenshot]

4 Relating Cognitive Psychological Findings to CAD

CAD systems have made strides over the last 25 years to make the designing of products easier and more intuitive. Companies have been integrating new analysis tools and automation into their products to aid the designer (e.g., Solidworks' fluid flow analysis, and AutoRouting and CREO 3.0's Design Exploration Extension that provides the capability to explore and save design alternatives without committing any changes to the original model [18]). Whether or not these enhancements support the solving of ill-defining problems during the design process remain empirical questions. This section make provides an initial interdisciplinary integration by examining the cognitive artifacts such as functional fixedness and problem fixation in the context of SolidWorks and CREO 3.0 functionalities.

SolidWorks as a Cognitive Tool. SolidWorks is a highly sophisticated drafting tool that supports 2D and 3D creation of design images, libraries that support prototypes of objects to reduce the need for "drafting from scratch", the automation of geometric problems such as layouts and path design. It may be argued that such tools provide cognitive support by reducing the workload of the user: they allow the design engineer to construct less during object creation by selecting a prototype and to think less or differently by disengaging from the solutions' reasoning process by selecting from automatically generated geometric solutions.

In the context of functional fixedness and solutions fixation, the interaction with object organized libraries has the following implications for the information processing of the design engineer:

The artifacts of functional fixedness seem to be preserved libraries that are organized by object type and to some extent by primary object use. Object types do not prompt the user with usage options or alternatives and that they are organized by primary use reinforces functional fixedness and lack of consideration for alternatives. The current level of implementation does not provide the user with alternative functions or usage of the object, or the capability to search by functionality. Likewise, since functionalities are not available, cross-referencing of multiple usages for the same is not an option. The question arises how functional fixedness can be alleviated in the context of design libraries rather being reinforced.

The automation of solutions appears as a time saving innovation by alleviating workload. However, it can be argued that this feature shifts the designer's task from creation and productive thinking to a selection task which may or may not be supported by well-reasoned analyses to determine the best option. While automation may alleviate the fixation on a single solution, it introduces complexity and choice options while detaching the engineer from the reasoning process. This raises the issue of reliance and trust in automation and to what degree automation can reasonably support the creative process of problem solving, without impairing human cognition. This topic awaits investigation and implications for the design process are likely profound.

4.1 Creo 3.0 as a Cognitive Tool

CREO 3.0 provides a number of sophisticated modelling and simulation tools, as well as vendor libraries and workflow management. It includes automation features and libraries similar to SolidWorks and the implications of these features for the occurrence of Functional Fixedness, creativity and reasoning need not be duplicated here. In addition CREO offers the Design Exploration Extension (DEX) a version tracking system that allows the designer to move back and forth between design alternatives; it seems possible that the facilitation of version tracking and the ability to preserve and track multiple solutions unencumbers the design engineer who wishes to explore alternative solutions without losing track. In that sense, DEX may alleviate working memory limitations and aide retrieval. Moreover, the memory extension provided by DEX could diminish the occurrence of solution fixation by implicitly supporting the memory of design engineers and reducing the workload associated with managing alternatives. Whether CREO users are less likely to exhibit solution fixation is an empirical question.

5 Cognitive Tools for CAD Using Function Based Retrieval

To capture the basic reason of a design, the designer's reasoning and design development must be understood in addition to generic human information processing artifacts.

Over the last 30 years, design cognition has been investigated by a small subset of mechanical, industrial, and electrical engineers, and computer scientists who have limited training in psychology. At the same time cognitive psychologists with limited or no training in engineering have investigated creative problem solving. It is easy to see that both research areas are highly related and that interdisciplinary investigations would be positioned optimally to address the underlying questions of design cognition. However, to date studies how to support the problem solving of the design engineer using the CAD system remain scarce and the implementation of tools that aide designers offers greater enhancements.

It been argued [1] that to integrate design needs into a CAD system various important aspects must be obtained and preserved:

1. The ability to track, capture and store design engineering concepts as they are developed along with the design reasoning (e.g., why, how etc.);
2. The ability to track all design solution possibilities and supply comparisons and advise, and have the ability to learn new solutions with the design engineer's assistance;
3. Standardized components are already are integrated in CAD systems (e.g., screws, bolts, belts, bearings, etc.), but the potential functionalities of these components need to be included and supplied with respect to their potential functionality;
4. The ability to retrieve any previously designed feature, part or assembly along with known functionality and design reasoning (and design history) of a given a component, and when new functionality is devised that this too is added to the component's stored database design reasoning information. In other words, the CAD system must be able to obtain and preserve the design reasoning while the design process is underway, while saved solutions need be retrieved to the CAD system through the functional parameters of the design and be able to transfer the retrieved solution's information, and capture the reasoning or intent of the design during development.

It is easy to see that design needs 1, 2 and 3 are mostly addressed by current systems. With respect to need to retrieval (item 4), Wood [1] was the first to develop a function driven mechanical design solution library that was capable of being implemented in an object-oriented or relational database. This system was targeted as a design assistant and advisor for the plastic injection molding domain, but was developed for other applications such as sheet-metal or casting designing. Wood's system (1) preserves the information of interfacing features within the product's database, (2) maintains a database of features with their fundamental properties and corresponding functions used by experienced design engineers, and (3) transfers the information within the solution's database to the design under development [1]. Wood also developed the structure called a "function-object" that is used as the search tool for his developed library that also serves to "maintain functional information of the solution that relates-to or interacts-with other objects" [1]. Wood's system documented plastic injection primary feature selection from the functions that drive a product's development or in other words Form follows Function. As stated by [1, p. 2].

"The use of functions for the search for solutions is not new, prominent design theory researchers have suggested solution library contexts revolving around complete design solutions. Other researchers have investigated designing-with features by using feature-based solution libraries… These investigations are relevant because they are the first step towards designing with features, but they either have not made a complete use of the functional attributes or have not modelled the entire solution in a functional way."

To summarize Wood's findings, the capturing of the basic reasoning of how and why a design engineer designs a product is necessary to fully preserve and document an object or object assembly. Therefore, capturing design information and being able to reuse these objects through a retrieval system in a CAD system requires different types of information transferal and preservation than those traditionally used. The design engineer develops and retrieves solutions through functional properties, transfers the retrieved solution‘s information, and consequently captures the design rationale or intent of the design during development. This approach is likely to support analogical problem solving and alleviate functional fixedness by preserving the reasoning and making a variety object uses available during the design process.

Overall, it seems that much empirical research remains to investigate the complex interaction between the design engineer and how to enhance CAD to provide optimal information processing and problem solving support. In addition to the function based design as a cognitive tool, other considerations that require investigation of the relationship between the representation of the design and design engineer's actions must take into account the aspects composing a design situation. For example a design engineer's design creativity using 2D or 3D shapes depends upon the discipline in which the designer is trained [19]. Similarly, [20] noted that different levels of abstraction (where cues for idea generation are represented) stimulate creative design outcomes differently depending on whether the designer is an expert or a novice. Additionally, different designers undertake design tasks in different ways ending-up with different designs even when given the same design specifications, and the same designer is likely to produce different designs at later times for the same specifications. The relationship between design representations and design actions is complex. Consequently, future cognitive CAD tools need to be sensitive to the diversity of experience, interpretation and goals of the users.

6 Conclusions

In the current paper we approached the complexity of the interaction between the design engineer and the CAD package from a cognitive psychological processing perspective. We conceptualized the design process as the creative solving of an ill-defined problem and integrated cognitive psychological findings with the state of CAD. Current software supports a number of design needs however it falls short of enhancing design cognition during ill-defined problem solving. Wood's function based reasoning architecture is presented as an approach to a cognitive CAD tool that alleviate functional fixedness and enhances analogical problem solving. Other interdisciplinary research domain should address individual differences in experience, training, and user goals. We leave the exploration of these topics to future papers and the implementation of current and future research findings in the capable hands of software *design engineers* as a somewhat ill-defined problem.

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