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Computerizing Conceptual Design without Hindering Creativity

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ABSTRACT

Recently, attempts to computerize and automate the engineering design process have taken the front stage. Indeed, theory and applications suggesting novel methods in utilizing computers to aid in the design process have been suggested. These suggestions range from number-crunching and storage techniques to ones that claim artificial intelligence whereby a computer can suggest new designs based on a pre-defined set of specifications. This paper focuses on the conceptual (synthesis) stage of the design process, i.e. establishing the requirements, the product concept and finally the solution concept. These steps complete the conceptual design of a given product and this paper examines the potential of these steps to be developed as a computer-based system, without hindering the creative process. It was observed that whilst humans can think with four different thinking styles, computers predominantly process information in two. The remaining two thinking styles that computers lack account for creativity and innovation in humans. Also identified in this paper was the fact that all four thinking quadrants in the human brain need to be utilized in order to produce an innovative design. This led to the conclusion that with current computer technology, it is impossible for a computer program to generate innovation, even though much research has recently focused on artificial intelligence and genetic algorithms. A computer-based system was developed to capture, index and retrieve information in an organized and prioritized fashion as well as guide the designer through the systematic process.

Keywords: conceptual design, systematic design, creativity in design, cognition.
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1. INTRODUCTION

Focus towards formalizing the design process at an early stage has been growing at a rapid pace over the last few decades [13,14]. A systematic design process is a sequence of events and a set of guidelines that helps define a clear starting point and takes designers from visualizing a product in their imagination to realizing it in real life in a methodical manner – without hindering their creativity. Several such design methods have been proposed. Although noticeably different from each other, they all essentially revolve around the same following basic stages:

1) Customer Requirements: This is the first stage of the design process. It is essentially a wish list that a customer would like to see in a given product. These requirements would be represented as a prioritized list. e.g. A chair that is comfortable to sit on.
2) Product Concept: This next step defines what the product will do in technical terms. At this stage, the design is solution neutral stored in that it avoids the use of possible design solutions or outcomes being made. This is done by having a prioritized list of Specifications or Functions. A typical specification is represented as a verb/noun phrase function e.g. Provide seat area.
3) Solution Concept: This is essentially the conceptual solution or outcome that the designer has decided as optimal in addressing the Product Concept. This is represented in the form of Subsystems, whereby each subsystem can represent a particular technology in addressing a set of specifications.

4) Embodiments: It is widely known that a given concept can be implemented using different parts. Embodiments are essentially parts trees that form the parts and subassemblies of the product.
5) Detailed Design: This is where the detailed aspects such as material selection, dimensioning and tolerancing are made. It also consists of the detailed Geometric Models which is used for computer simulation and optimization.

Recently, attempts to computerize and automate these design steps have taken the front stage. Indeed, theory and applications suggesting novel methods in utilizing computers to aid in the design process have been suggested. These suggestions range from number-crunching and storage techniques to ones that claim artificial intelligence whereby a computer can suggest new designs based on a pre-defined set of specifications. This paper focuses on the first three stages of the design process listed above, i.e. establishing the requirements, the product concept and finally the solution concept. These steps complete the conceptual design of a given product and this paper examines the potential of these steps to be developed as a computer-based system.

The ability to design (especially at the concept stage) is a combination of science and art [11] and computers are not known for their artistic ingenuity. Conceptual Design involves creation in order to satisfy a need and this clearly relies on the ability to be creative. In order to develop a conceptual design system that does not hinder this creative process, then one of the following two points must be achieved:

1) A computer-based conceptual design system is developed that is capable of creative and innovative ‘thinking’ (or processing).
2) A computer-based conceptual design system is developed that assists the human designer but does not attempt to be creative and must not interfere with the human creative thinking process.

These two options both raise several interesting questions:

- Are computers capable of being creative? Do computers have the ability to innovate?
- How do humans differ in their thinking process from computers?
- How are humans creative? Can creativity be learnt/trained by humans and if so, can this learning process be captured and ‘taught’ to computers?
- Can a computer entirely replace a human designer in the design of a new and innovative product? If so how? If not, then is it possible to create a computer-based system that replicates the design process whilst allowing the human designer to still be creative (option 2)

These questions open up several large areas of research, which includes research in cognitive science, computer science, and design theory and methodology. An understanding of all three areas can provide the foundations for developing a human-based, computer assisted creative design system.

2. CREATIVITY AND COGNITIVE FUNCTIONS

Cognitive science research on creativity began with Chomsky [4] who identified that it was necessary to address internal mechanisms to account for high-level cognitive functions. Since then, several models have been proposed [18] on how the human brain works. One of the well-known models is the Herrmann model [12,11]. This model divides the brain into a four quadrant brain dominance model (Figure 1). These quadrants are located in the left and right hemispheres (left and right brain). Herrmann broke down each of the four quadrants as responsible for different characteristic thinking styles as follows:

1) ‘A’ quadrant – The left cerebral hemisphere in Herrmann’s model is associated with logical, analytical, and quantitative thinking.
2) ‘B’ quadrant – The left limbic system is associated with sequential, organized, and detailed thinking.
3) ‘C’ quadrant – The right limbic system is associated with emotional, sensory, and interpersonal thinking.
4) ‘D’ quadrant – The right cerebral hemisphere is associated with visual, intuitive, and innovative thinking.

Herrmann determined that whilst individuals will have a combination of all four thinking styles, each individual will have preferences in certain quadrants. Haik identifies this as a result of the each unique native personality interacting with family, education, work, and social environments. Further research into creative thinking (quadrant ‘D’) has led to the development of the Geneplore Model [7]. This model offers a framework to understand how human thought evolves during creative processes. The Geneplore Model identifies two phases of creativity:

1) The generative phase. In this phase, a mental representation is constructed. This is known as a pre-inventive structure having various properties that promote creative discovery.
2) The exploratory phase. In this phase, the various properties from the generative phase are exploited in which one seeks to interpret the pre-inventive structure in meaningful ways.

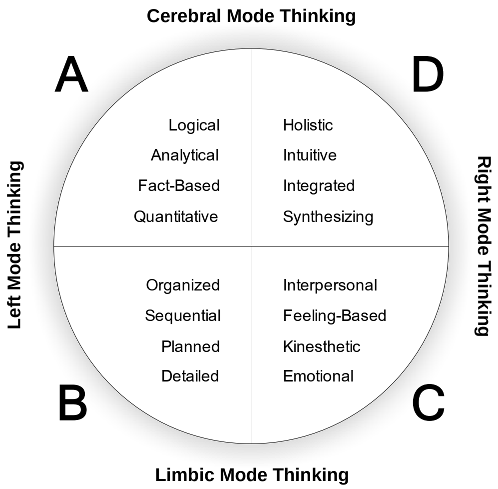

Fig. 1: Herrmann's four quadrant brain model.

Finke et al. [7] characterized pre-inventive structures as representations of novel visual patterns, object forms, mental blends, category exemplars, mental models, and verbal combinations. Benami and Jin [2] identified that what these structures have in common is that they are initially formed without full anticipation of their resulting meaning and interpretation and that they are distinguished from the final externalized creative product, which, in contrast, is often fully interpreted. It is this interpretation that is able to arrive at radically different conclusions for the same given inputs.

3. CREATIVITY AND DESIGN

Haik [11] observed that there are three different types of designs: Adaptive Designs, Development Designs, and New Designs.

1) Adaptive design: This involves adapting existing designs and involves making minor modifications. Usually the conceptual and embodiment designs remain the same and modifications are made at the detailed design stage. This type of design involves hardly any creative thinking and would focus on utilizing predominantly the 'B; quadrant of Herrmann's thinking styles by following a sequence of steps and maintaining a project schedule. Some aspects of quadrant 'A' will probably also be required.

2) Development design: The designer starts from an existing design, but the final outcome may differ markedly from the initial product. Considerably more scientific training and design ability are needed for development design. As opposed to adaptive designs, development designs would be modified at both the embodiment and detailed stages of the design process, with the conceptual design usually remaining the unchanged. This type of design would require utilizing predominantly quadrants 'A' and 'B' of Herrmann's thinking styles as a more logical and analytical approach is needed. Aspects of quadrants 'C' and 'D' will probably also be required

3) New design: For a new design, all stages of the design process have yet to be performed. This type of design is the most difficult and generating a new and innovative design requires the most extensive use of all four quadrants of Herrmann's brain dominance model and would be expected to be utilized as follows:

- The ‘A’ Quadrant would be utilized for analyzing the needs, indentifying the specifications and in general executing the scientific and technical aspects needed to produce the design.
- The ‘B’ Quadrant would be utilized whilst following the sequence of steps dictated in the systematic design process as well during the project management aspects of the design. It would also be used to capture, retain and organize the information which would then be analyzed using the ‘A’ Quadrant.
- The ‘C’ Quadrant relies on emotional, sensory and interpersonal thinking styles and this is also vital for the success of a design project as it is the ability to interact with all those that are involved with the project (including the customers, design team, manufacturing and marketing people, etc.,) that is key to its success. Emotions and sensations are also extremely important ingredients in assessing what the desires of the customers are and how they will react to the product, which can be emotional and analytical in nature.
- Finally, it is evident that the ‘D’ quadrant is vital to conceptual design as it is the one associated with visual, intuitive and innovative thinking, all major elements of great designs and designers; both scientifically and artistically. The artistic and aesthetic aspect of design should not be under-looked, which predominantly use both the ‘D’ quadrant for visual thinking and the ‘C’ quadrant for emotional and interpersonal elements essential to art and aesthetics.

The need for all four quadrants of the brain to be activated at different stages of producing an innovative design is one of the reasons people find difficulty and challenges in designing since they predominantly think with quadrants that they favor and have been employing for years. To train them to ‘activate’ and use the least preferred quadrants becomes the challenge. Successful teams will have people with varying thinking styles and preferences and are as a unit are able to employ all four styles in order to achieve a better result in a shorter time span.

4. CREATIVITY AND COMPUTERS

If Herrmann’s ‘thinking styles’ were related to computers, it is fair to stipulate that computers are predominantly focused in the ‘A’ and ‘B’ quadrants. The only elements from the ‘C’ and ‘D’ quadrants that computers can claim to utilize are the visual aspects and some sensory elements. The visual aspect is arguably not a thinking/processing style but rather a form of communication and any sensors that are used by a computer, the data captured is immediately processed to the ‘A’ and ‘B’ quadrants. Sensors here are not used to invoke an emotion, which is in contrast to humans.

So why can’t a computer operate in the ‘D’ quadrant? The Geneplore Model mentioned earlier identified that one of the main factors driving creativity is the interpretation of the various properties of pre-inventive structures. It is this interpretation that provides the radical and alternative solutions that define an innovative conclusion to the same set of inputs. Many ‘interpretations’ of computer programs will follow an analytic, sequential and quantitative path that will lead it to the same conclusion every time. The closest techniques that resemble this cognitive process are genetic and evolutionary algorithms [3, 8, 17, 19, 25, 26]. Genetic algorithms are inspired by Darwin’s theory of evolution and utilize an evolutionary process to find a solution by searching for answers using a population of prospective solutions. Solutions from one population are taken and used to form a new population (expected to be an improvement over the old population). Solutions which are then selected to form new solutions (offspring) are selected according to their fitness - the more suitable they are the more chances they have to reproduce. This is repeated until some condition (for example number of populations or improvement of the best solution) is satisfied. Close inspection of the technique reveals that the algorithm is still not ‘innovating’ or being ‘intuitive’ and is still firmly rooted in the ‘A’ and ‘B’ quadrants or analytical and quantitative processing. As such, this method has proved successful and popular in optimizing solutions, but still falls short when attempting to create and entirely new one.

By referring to the different types of designs identified in the previous section, it becomes evident that with the technology that currently exists, computers are unable to produce new and innovative designs as it is outside their scope of thinking/processing styles. Computers may be able to suggest different embodiment designs for development designs by providing processing abilities in the ‘A’ and ‘B’ quadrants. However it would seem that computers are best suited to adaptive designs whereby the conceptual and embodiment designs remain the same and changes are made primarily at the detailed stage (e.g. materials, dimensions, manufacturing processes, etc). Indeed, programs that simulate and optimize designs based on pre-defined objectives already exist and are widely used.

This does not mean that computers are not helpful at the early stages of the design process since both 'A' and 'B' quadrant style thinking are still required in these stages. This implies that computers can still be utilized efficiently whenever a particular thinking style is needed in which they are able to work in, suggesting that a computer based conceptual design system would involve automating the sequences of steps, as well as capturing, storing, and organizing information for future access. Computers would also be used for project management and quantitative methods that are needed at the conceptual design stages. Finally a computer is a good way of communicating and presenting ideas visually to the designer and this aspect can be exploited as an aid to the designer. Caution should be used on the last point however, as one of the elements of creative cognition is the ability to interpret different structures. It is vital that computers do not guide the designer towards a particular interpretation, whether visually or in any other manner. Other research confirms this hypothesis and states that computers are well geared for design knowledge capturing and reuse. Duffy et al. [6] researched existing design software and described these developments. They grouped design based computational issues under the following three categories:

1) Indexing and information retrieval
2) Knowledge utilization
3) Exploration and adaptation

It is interesting to note that they failed to find any computational issues that dealt with innovation but rather areas which deal with a computer program's ability to function in the 'A' and 'B' quadrants. Expanding on the second issue, Duffy et al observed that three main types of knowledge modeling [9,5] and utilization techniques have been developed. They are:

1) Case Based Reasoning
2) Model Based Reasoning
3) Plan Reuse

Case based reasoning [15,16] in design involves the storage and reuse of past design cases in new designs. It encompasses approaches to representing, indexing and organizing past design cases and processes for retrieving and modifying selected instances. Case Based Reasoning provides a past design as a starting point of a new design. They are directed at the selection and modification of appropriate instances. Model based reasoning involves the development of knowledge models upon which to base new designs. Model bases represent general knowledge and case bases represent specific knowledge. Plan reuse involves the rationale behind design decisions and the replaying of a suitable design history during a design activity. Plan reuse aids the designer through the series of decisions that further the design process and consequently generates the new design solution.

So it has been observed that classifying computers into 'thinking/processing styles' demonstrates their limitations and provides justification as to why programs that have been developed to use some form of artificial intelligence in the automatic generation of ideas, have so far failed to produce something that is novel and unique to itself. Computer programs inherently force the computer to assimilate design in its limited thinking/processing quadrants. Attempts to counteract any shortcomings have so far been to provide previous case studies (case-based reasoning) and vast databases of knowledge (knowledge-based design) for the program to refer to. However this is still using the same analytic, organizational and logical thinking quadrants, so true innovation becomes nearly impossible. Even advanced techniques such as genetic algorithms have severe limitations in when attempting to 'create'. It is fair to stipulate then that a good computer-based conceptual design system should focus entirely on automating the sequence of events that make up the design process, whilst previous case studies and knowledge bases can be integrated to provide for developmental and adaptive design as well as helping to optimize a finalized design solution.

5. COMPUTER-BASED CONCEPTUAL DESIGN

The previous three sections examined creativity from a human cognitive aspect and related this to how computers operate and process information. This section discusses the initial phase of development of a computer based conceptual design system. In developing such a system, the main focus was to create an environment that allowed input by the human designer predominantly in the 'C' and 'D' thinking quadrants, (i.e. emotional, sensory, and interpersonal thinking, as well as visual, intuitive, and innovative thinking), whilst manipulation and presentation of this information was processed by the computer using 'A' and 'B' thinking quadrant qualities, i.e. logical, analytical, and quantitative processing as well as sequential, organized, and detailed analysis. This allows taking full advantage of both human and computer processing strengths.

As a result of this reasoning, several important issues needed to be considered when transforming a proposed methodology or system to a computer program. Importantly, it should not be a direct transfer as this may, and usually will be confusing to the user/designer. The ways in which computers process information and the thinking styles of humans needed for design will not always corroborate. A spreadsheet, for example, is not how a person would usually perform manual calculations. However, it should not also be completely different so as to alienate the designer and make it a burden to use. The application should therefore try to implement the proposed methodology, whilst attempting to remain loyal to how a designer would 'design' a product. Such a program achieves the following:

1) Allows input of designs in a manner consistent with the thought process of a designer.
2) Stores new designs under the proposed structure within the Design Model.
3) Allows the partitioning of existing past designs and subsequent storage as mentioned above
4) Allows for easy retrieval of past designs at any stage of the design process
5) Provides an indication as to the success of each stage of the design to help in the decision of reusability.
6) Provides a means for easy reusability and modification of past designs to suit a new one.

Figure 2 presents a computer-based system that addresses these issues. DFD was developed by combining the advantageous features of the following:

(a) Quality function deployment (QFD) [23,22]
(b) Concurrent engineering
(c) Design models and methods
(d) Elements of product modeling
(e) Computer-aided design and data management

In Level 0, the user defines the various design methods (design tools) he/she is expecting to use during the design process. This would also be the user interface of the computer system. Level 1 represents the design model as the minimum prescribed path. Level 2 houses the various Design Methods such as morphological analysis charts, CAD, finite element analysis depending on which stage of the design process is being addressed in level 1. Level 3 contains the supporting databases, rule bases and knowledge bases.

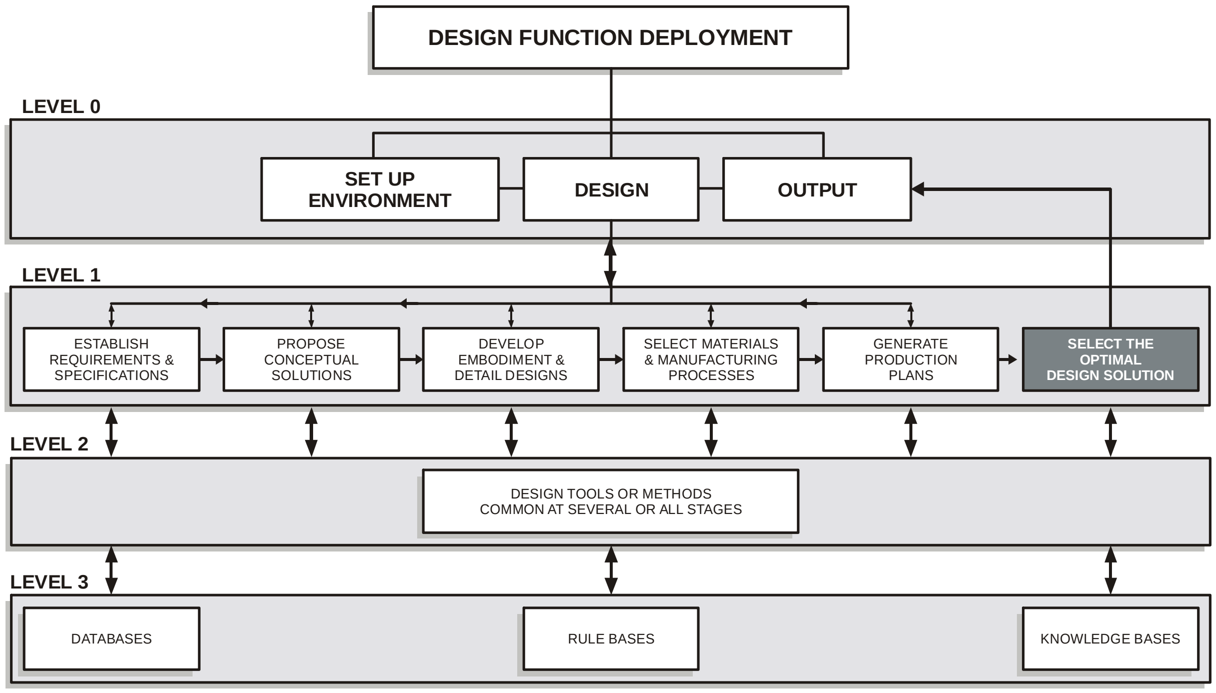

Fig. 2: Computer based design system.

A program built around a database-structured framework was created and deemed to be suitable to take full advantage of both human and computer processing skills and interfacing. It was decided to base the database around a relational table structure so as to integrate easily with other databases in the designer's environment. Each piece of information is stored in a separate table and then relationships and links are created to avoid repeated information and inefficiency. This also allows for greater flexibility. Although the program used MS Access to generate the tables and store the information, all the links and queries were stored within the Design Reuse Program using the Structure Query Language (SQL) to aid easy portability to other databases. This means that the all the data structures can hence be integrated with a company's existing database and linked further down to information such as suppliers and customers.

The Database Management System accomplishes the following:

1) Structures and Stores new and old designs using the underlying Design model described earlier, i.e. Product Concept, Solution Concept, Embodiments and Detailed Designs. It also provides a way to assess quantitatively how each stage of the design process is being addressed, using house of quality charts used in QFD.
2) Retrieving, viewing and modifying any stage of the design in an efficient manner
3) Reusing any item of a design into another design.

In order to aid indexing and information retrieval without hindering the human thought process, a method was devised that allows seamless capture of information whilst a designer is in the process of designing a new product. Sivaloganathan et al. [24] show through a practical case-study that when designing a new product and that not all the information is immediately available to the designer, he/she will revert to traditional-based design process. This includes brainstorming, sketching and using general experience. However, once this information becomes readily available, the designer is keen to store this information in a structured fashion, so that he/she has a proper record of the design for reporting and reuse. This has been provided for the designer in the following ways:

To address the 'C' and 'D' thinking quadrants, a Designer's Logbook Environment was developed for capturing the designer's thought process. This is the main reference point for the designers within the software and is where they will spend most of their time in the early stages of the design process. It is intentionally similar to a traditional designer's 'logbook'. The information entered naturally by the designer is automatically stored in a database in the relevant data structures, which allows processing it in the 'A' and 'B' style quadrants, using quantitative measurements (e.g. House of Quality Charts) as well as knowledge and case-based existing information. Figure 3 illustrates an example of this environment. Each tab for the notebook represents a different stage in the design process. There are several pages under each stage to enable the input of sketches, comments and ideas. Also available to the designer is a database search facility to view previous past designs for possible reuse.

Fig. 3: Computer based design system – notebook environment.

Once the designer is ready to start structuring information for the design, it is possible to access at any time, screens to feed in the specifications of the product. The designer will be presented an opportunity to refine the specifications to precise engineering specifications. An importance rating is then asked from the designer by selecting one of the listed options. It was intentionally decided not to present the designer with any charts at this stage, in order not to confuse him/her. The forms are presented in a list fashion and it is possible to pick previous specifications that have been used before as they are always presented in a separate list box. Each stage of the design process is presented in a similar fashion, so as to keep consistency and hence familiarity. Figure 3 shows example screenshots of specifications input.
Once each stage has been finished, an option for entering ratings for each 'row' and 'column' of the corresponding chart is presented. This is not presented in a table format as it can become confusing and tedious for the designer when designing complex products. Two list boxes are available, one for the rows and the other for the columns. The designer selects the relevant row and respective columns and selects a rating.

After the designer has fed this information, a chart is then created, showing a sketch of the relevant stage along with its absolute and relative importance ratings. A search facility is available at any stage of the design process and the database is searchable by any data model output (Specifications, Functions, Embodiments or Part). Search results will display where the search criteria have been used before as well as their relevant ratings. It is also possible to view further down or up the design process to see how this item is related throughout the entire process. It is then possible to import any piece of the information or all of it into another design. The program also keeps track of the work the designer is carrying out and will automatically search new information being entered for similar past designs. It then points this out to the user in a 'wizard' form and displays the relevant project, date, design information and ratings, with the option of importing this information into the current project.

The system helps to guide the designer through the process as well as provide a place for capturing, indexing, and retrieving information. The system is also able to analyze the information that has been captured and present it to the designer in a prioritized fashion based on proven qualitative and quantitative methods [22,23,11] in conceptual design theory. As this system has not interfered with the generative or exploratory stages of creative cognition, it has not hindered the process. It might even be argued that by structuring and organizing the information in a clear manner, the human designer is left more time to focus in the 'C' and 'D' quadrants and hence encouraging creativity.

6. CONCLUSIONS

This paper explored creativity from a cognitive perspective and related it to how computers think. It was observed that whilst humans can think with four different thinking styles, computers predominantly process information in two. The remaining two thinking styles that computers lack account for creativity and innovation in humans. Also identified in this paper was the fact that all four thinking quadrants in the human brain need to be utilized in order to produce an innovative design. This led to the conclusion that computers are not able to innovate, even though much research has recently focused on artificial intelligence and genetic algorithms. A computer-based system was thus developed to capture, index and retrieve information in an organized and prioritized fashion as well as guide the designer through the systematic process. Future directions with the computer-based system are envisioned to include the computer identifying the next steps required within the design and identify whether it or the human designer would be better suited to complete the relevant tasks. Also, further implementation of case-based and knowledge based design tasks needs to be integrated within the system. Finally, integrating this system within an overall computer-based design framework is needed to assess the overall efficiency and end results.

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