

CAD Usage in Modern Engineering and Effects on the Design Process

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Computer-aided design (CAD) is widely used by engineers in the design process as companies transition from physical modeling and designing to an entirely virtual environment. Interacting with computers instead of physical models forces engineers to change their critical thinking skills and learn new techniques for designing products. To successfully use CAD programs, engineering education programs must also adapt in order to prepare students for the working world as it transitions to primarily computer design work. These adjustments over time, as CAD becomes the dominant method for designing in the engineering field, ultimately have effects on the products engineers are creating and how they are brainstorming and moving through the design process. Studies and surveys can be conducted on current engineering students as well as professional engineers to determine how they interact with CAD differently from physical models, and how computer software can be improved to make the design process more intuitive and efficient. This paper will summarize the findings of previous research on the effects of CAD on engineers and the products they create and suggest potential improvements to computer software interfaces that could benefit the design process.

Background

Prior to the invention of computers, engineering design work had to be done on paper by hand. Without calculators, any math or analysis also required knowledge of various topics and expertise in complex problem solving. Design iterations would also have to be drawn on paper in 2D, offering a more limited view of the design for a product before production began. Prior to CAD, prototyping also had to be done physically, which required materials and more time from

engineers for the construction of models. Computer-aided design changed the world of engineering by reducing the time and resources required in the design process as engineers transitioned to working in a virtual environment.

CAD systems first appeared in 1969 at MIT in the form of “Sketchpad”, a software designed by Ivan Sutherland. This 2D software was used by engineers in industry and inspired the creation of other CAD software, with the first 3D software being created in 1972. By the 1990s, 3D CAD software had become widespread enough that it could be used on personal computers, and since then the use of CAD software has only grown (Brown, 2009).

Computer-aided design was initially introduced to companies as a method of reducing costs by simplifying design drawing. Over time, CAD has been driven to integrate factors outside of just drawing such as marketing, engineering, and manufacturing, in order to lower costs while producing higher quality products. As CAD has evolved and become more widespread, the functions of CAD software have expanded to include performing calculations, creating design parameter databases, generating program controls, providing realistic visuals in 3D, and offering graphic simulation capabilities (Tan, 2006). With CAD now reaching into so many subsections of engineering and the design process, there is an inevitable impact of the software on engineering jobs as well as engineering educations that attempt to produce students best prepared for the workforce.

Existing Studies

By the nature of computer-aided design itself, engineers are forced to interact differently with it than they would with physical models. Physical experiments or testing will prompt different responses from the operator than an entirely virtual environment or simulation. Because

of the stark contrast between CAD and physical modeling and engineering, there have been many studies on a variety of aspects of CAD software and the design process as it incorporates CAD. In order for companies to invest funding into training employees with CAD software and paying for licenses, it must be known if CAD is actually beneficial to the design process and truly cuts costs. It is also vital to know how the emotional reactions of engineers change when interacting with physical models as opposed to computer software, and what kind of impact this could have on the products engineers create. If CAD software is unintuitive and frustrating to use, it can become the object of an engineer's work, instead of the designing itself (Suchman, 2005).

Through an analysis on these studies and surveys, it can be summarized what the impact of CAD on engineering design and education is, and how the design process itself has been changed by computer-aided design software. Potential ideas for improvement of these types of software can also be identified in order to improve CAD usage for engineers so that the design process integrates designers best with their virtual work, instead of distancing them from it.

CAD in Engineering Companies

Especially at the beginning of CAD implementation by companies, questions were raised over the actual benefits of using computer software over physical designing and testing. Opportunity arose to study the benefits of computers in the design process to encourage companies to use CAD software and invest in training engineers with such systems. Concurrent engineering is a term used to refer to the integration of product and process designs in the early stages of product development (Tan, 2006). This type of engineering reduces time required by the design process and can also promote cross-functional teamwork during modeling and

prototyping. Computer-aided software promotes concurrent engineering by allowing team members to work on separate parts or stages of one design at the same time as each other.

CAD also provides the opportunity to easily synthesize information from a model or design, which can then be shared among different functions of the full product development network (Tan, 2006). Tan conducted research using a survey for manufacturing executives on the benefits of CAD keeping this definition of concurrent engineering in mind. This study revealed that there is indeed a connection between CAD usage and concurrent engineering at manufacturing firms, and that firms with higher product variety implemented CAD more for controlling costs. Research like this confirms that CAD has a positive impact, at least in the eyes of manufacturing firms, by cutting costs and saving time through integration of various fields and types of engineers in one design or model.

In addition to broad surveys of many manufacturing firms, there has been separate research into the specific interactions of a small manufacturing firm with 3D CAD programs and finite element analysis (FEA) software. A study from Elm examined a small manufacturing enterprise and the effect of CAD software on the design and engineering processes within the firm. A case study that focuses specifically on a small firm and the interactions of engineers with 3D CAD software is beneficial in determining how engineers interact differently with computer-aided design software as opposed to earlier forms of design technology. The case study examined productivity of the manufacturing firm and how design techniques were altered for CAD and FEA tools. It was observed that adoption of the new technology was successful but demanded engineers to learn new skills in order to be successful. The research also identified that changes in the design process may occur when engineers switch from 2D design software to 3D CAD programs as skills are learned and non-intuitive issues arise with the software itself

(Elm, 2003). From this study it can be observed that CAD adoption at individual engineering firms is successful at improving productivity but requires engineers to learn new skills and adapt to new ways of designing. This could end up having an effect on the products they create as the design process is forced to change.

Studies on Engineers

To better understand how engineers specifically interact with and react to computer-aided design software, surveys can be conducted on CAD users instead of entire companies to study how a virtual environment impacts their creative design process. Engineers are vital stakeholders in the design of CAD software, and observation of their interactions with CAD can point out ideas for how programs can be improved in order to optimize the design process and improve the products that engineers design.

Positive and negative impacts of CAD on the engineering design process have been identified through studies on interactions of engineers with each other and the models they create. Robertson and Radcliffe (2009) conducted a study on participants embedded in small engineering design teams for long periods of time to examine how CAD software impacts engineer's "creativity". They define "creativity" as: "ideas or concepts which are both novel and useful, or unexpected connections between seemingly unrelated ideas, concepts, or solutions." The study revealed a series of findings on the impacts of CAD on the design process. Computer designing software was shown to clearly enhance visualization and communication between members of the engineering team, while creative thinking and ideation were found to be bounded as a result of technical bugs and the tendency to fixate on initial design ideas. The research concluded that teams that worked with each other while sketching and discussing during the design process were able to be more creative. It is clear from this study that CAD software is

having an impact on engineers as they work through the design process during product development. With identified negative impacts of CAD, potential solutions to these issues could be proposed, such as promoted communication and better platforms for sketching and discussing with teammates before diving into prototyping.

Emotional reactions of engineers can be measured while working with CAD software. Liu et al. conducted a study to quantitatively measure and observe the emotional reactions of engineers and CAD operators while using CAD software. Psycho-physiological signals such as EEG and ECG signals were recorded and analyzed as operators work with CAD interfaces. Correlation is shown between certain signals and emotions of CAD operators and certain tasks that were being performed using the software (Liu, 2014). This research confirms then that there is a link between the emotional state of engineers and the usage of CAD systems. This will in turn have an effect on how engineers design, as their creative thinking process will be affected by their mental state during the design process. A study like this is vital in showing how there is room to improve CAD software platforms. Any tasks that were associated with negative emotional reactions from engineers could be changed to be made more intuitive or easy to use. Changes to software like this would improve the experience of engineers when designing, improving the products they create as they are more able to focus on the creative design process and less on any bugs or issues with the CAD software.

Software issues are not the only limitation to CAD design programs compared to traditional methods of designing engineering products. There are natural limitations that computer software introduces to the design process that don't exist with physical experiments or models. While it is known that computer simulations can save time and money for engineers and companies using them, computer designed geometry can cause difficulties when it comes to

communication between CAD and other models. There is room for improvement with CAD software when it comes to sharing information and being able to use this information in an iterative design process to go back and make changes to the initial model. A study from Heikkinen et al. (2018) observed interactions at 3 companies between the designers of CAD geometry and multidisciplinary information that could be added to the model. These engineers found difficulties with adding multidisciplinary information to the CAD models, and also struggled with issue that wouldn't arise with a physical model, such as software updates and tradeoffs between mesh quality and geometric simplicity. Issues such as those regarding the oversimplification of a model wouldn't occur in a physical setting, and highlight some potential issues with CAD software when compared to physical modeling. Like other studies, this research also looked specifically at the engineers using the software to identify these issues. This information shows how engineers that use CAD are vital in improving the programs and therefore improving the design process and ultimately the products that engineers produce for the general public to use or benefit from.

Opportunities for Improvement

Proposed ideas exist for ways to improve CAD software so that it is more intuitive for engineers and designers to use. Natural integration of computer aided design into an engineer's work would have positive results on the entire design process, allowing them to fully focus on their work and gain a greater perspective and knowledge of the product impact than physical designing could offer.

A study from 1993 by Tomiyama et al. identified the importance of functional design in the design process, and how CAD technology failed to support function during design.

Functional modeling is defined as designing and developing models of products or systems based on their functionalities. Functional analysis is critical in the design and development of complex engineering systems where many components may have completely different functions but operate in the system together (Zhao, 2018).

A new method called FBS (Function-Behavior-State) was proposed in order to support functional design alongside CAD software (Tomiyama, 1993). This topic remains relevant in current engineering and CAD technology, as a paper written by Zhao et al. in 2018 reveals. This paper identified that existing functional models are still ineffective in their goal of assisting designers in analyzing functionality during design of products and systems. Similar to the paper from 1993 by Tomiyama et al., a state-behavior-function model is proposed to represent components and functionalities of multi-state systems in computer-aided design software (Zhao, 2018). These two papers have identified an issue with CAD software that affects the design process: the inability of engineers and designers to design functional models, which then hinders their ability to communicate effectively across disciplines or generate concepts or ideas in the design process. Functional modeling is proposed in both of these studies using similar methodologies that use function, behavior, and state, to improve CAD software. There is room for improvements from CAD software companies to include these methodologies in their development in order to optimize the experience of software usage for engineers and to encourage communication between disciplines, easing and facilitating the design process for all involved.

Impact on Engineering Students

From the previous sections, an effect on professional engineers and work conducted by engineering companies is observed and confirmed. Naturally, as CAD software has become more integrated into the work of professional engineers at engineering companies, the education and training of engineering students at higher education institutions has had to adapt as well. As work with physical models becomes less common, while more and more students use CAD regularly in classrooms, the thinking process of new engineers produced for the workforce is changed from engineers who were trained with older, traditional methods. It is important to determine the effect that CAD in engineering education is having on how younger engineers think and design, and how the products they create will be different from those of engineers educated with physical models and experiments.

CAD software can be useful in engineering education, not only in preparing students for an engineering workplace, but also in supporting engineering research and education. A virtual environment encourages students to experiment and learn without the expense, hazard, and scale of a physical model of the same system. Xie et al. (2018) studied the effects of CAD in the classroom, identifying these benefits and also acknowledging that there have been suggested risks to students' abilities to creatively think and design. This study was conducted on high school students using CAD software, but the results can be applied to students of any age using these platforms for engineering education. The students used software to design a solar panel system for a house roof and were surveyed before and after the project to collect data on science and engineering knowledge. The research concludes that the students had positive responses to interacting with the CAD software, and learned science and engineering concepts (Xie et al., 2018). Studies such as these can show how students interact with CAD software as opposed to

physical experiments, and the benefits that come with computer-based learning in engineering education as opposed to the same lessons being taught with physical models.

I conducted a study on fellow engineering students with a variety of majors at the University of Virginia to determine the frequency with which CAD is used in engineering education of college students, and the impacts it had on the learning experiences of the students. An anonymous Google form was sent out to a large group of students of all ages, years, and experiences. Raw data from the survey is shown in the Appendix of this paper. From 16 student responses, it was found that 87.5% of those surveyed had used CAD before. The most commonly used software platforms were SolidWorks and Inventor, with each at more than 75% of respondents saying they had experience with the software. In order to gauge the frequency with which CAD is used in the students' education/workplaces, a question was posed about how much more computer-aided design was used instead of physical models.

It is clear from the data collected, these students primarily used CAD *significantly more* and *slightly more* than any physical equivalents. These two sections add together to equal 62.6% of the responses. This data is vital in determining how frequently CAD is used in engineering education or student workplaces, and reveals that, for these students, it is used far more commonly than any physical experiments or lessons.

The students were also surveyed on whether they preferred working with CAD or physical models, and with which method of designing they created better work. The responses to these 2 questions are interesting because they showed a clear contrast between preference for methods of design as opposed to what actually leads to better products. The question about preference reveals almost an even divide between CAD and physical models, while the question regarding quality of work shows that almost *all* participants (87.5%) believe they design better

work using CAD. Knowledge such as this reveals that engineering students value and learn from work they conduct using CAD software, and feel that it is more beneficial to the design process than physical experimenting and modeling.

To complete the survey, the students were asked to give suggestions on how CAD software can be improved. The responses given seem to indicate a desire for more intuitive and integrative design of CAD software. Students gave examples such as “constraints or suggestions that are more user-friendly” or “increased integration of FEA, dynamic modeling, assembly constraint limits, and tolerance analysis tools”. This open-ended question allowed students to give honest suggestions for how CAD can be improved, and issues were clearly identified by students that hinder the design process and lead to engineers and engineers in training becoming more focused on the software than on the model itself. The results from this study show that engineering students value CAD platforms in their engineering education and feel that computer software can improve their learning experiences and the work they design. Even still, issues were identified that exist with CAD software that could be improved upon to lessen the negative, distracting effect an unintuitive virtual environment can have on the design process.

Discussion

The survey conducted of engineering students at UVA serves to provide evidence that CAD is widely used in engineering education, and back up the claims made earlier in this paper regarding the effect of virtual design on the creative engineering process. Engineering students that participated in the study revealed the widespread use of CAD, and how it proved to be beneficial to their learning environment and led to the design of better products, both in professional and educational settings.

Existing studies confirmed that, like my survey suggested, there is a large impact that CAD is having on the workforce and engineering education as it becomes more prominently used in the design process. From these studies it can be summarized that the impact CAD has on the design process is mostly beneficial, with students more able to learn about complicated experiments or models, and engineers more capable of designing integrated systems with greater efficiency. The concurrent engineering studied Tan et al. (2006) was shown to have been greatly improved by CAD systems as opposed to physical modeling. There have also been some negative effects identified, such as a decrease in creative thinking and ideation being bounded as a result of having to focus on software bugs or issues over the design process. From the identification of these issues with CAD software, suggestions for improvements can be made.

The surveying of engineering students and engineers proved useful in generating suggestions for improvements to software platforms, such as increasing integration of various CAD fields like FEA and dynamic modeling. Research has also suggested for decades that adding considerations for functional design to CAD platforms would improve the design experience and lead to engineers creating better products. Ultimately, CAD has changed engineering education and work for the better, allowing students and engineers to become more involved in their work and produce better prototypes more efficiently, but there are areas where software can be improved to be even less of an obstacle to creative thinking for operators of CAD programs.

Future work could focus more on the use of CAD in engineering firms and companies. While the study conducted of UVA engineering students showed positive consequences of CAD use, existing research on engineers was less conclusive besides the confirmation of a virtual environment allowing for more whole-system integration. Studies could be conducted on

engineers already in the workforce who have worked both with physical models and CAD programs, to identify differences in the work produced and designed and any positive or negative effects. There is also room for research into how engineers who were never trained in their engineering education with CAD software have had to adapt to its implementation in almost all fields of engineering. For this population of older engineers, the use of CAD could have negative effects on the design process and products produced if there is a lack of adequate training and preparation.

Conclusion

This paper summarizes existing studies on CAD usage at companies, by engineers, and by students. A survey was also conducted of UVA engineering students on their experience with CAD and suggestions for improvement. This research is limited in that no suggestions for improved computer software could be tested on engineers or students. Future work could focus on testing the suggestions made in this paper to CAD software for better integration and intuitive design.

Appendix

Raw data from the engineering student survey.

Timestamp	Are you an engineering student (current or former)?	Have you used CAD (in any form) before?	What CAD software have you used?	Would you say CAD was used more than physical experiments or models in your education/workplace?	Do you prefer working with CAD or physical models?	Do you think you design better work using CAD or physical models?
3/24/2021 11:15:05	Yes	Yes, in class, Yes, for a job	SolidWorks, Inventor, AutoCAD	Yes, CAD used significantly more than physical models	CAD	CAD
3/24/2021 11:21:49	Yes	Yes, in class	Inventor	No, CAD used significantly less than physical models	physical models	physical models
3/24/2021 11:21:55	Yes	Yes, in class, Yes, for a job	SolidWorks, Inventor, AutoCAD	Yes, CAD used significantly more than physical models	CAD	CAD
3/24/2021 11:33:02	Yes	Yes, for a job	SolidWorks, Inventor	No, CAD used slightly less than physical models	physical models	CAD
3/24/2021 11:41:07	Yes	Yes, in class, Yes, for a job	SolidWorks, Unigraphics	Used about the same	CAD	CAD
3/24/2021 12:19:43	Yes	Yes, in class	SolidWorks, Inventor, AutoCAD	No, CAD used significantly less than physical models	CAD	CAD
3/24/2021 12:22:33	Yes	Yes, in class, Yes, for a job	SolidWorks, Inventor, AutoCAD	Yes, CAD used significantly more than physical models	CAD	CAD
3/24/2021 12:53:41	Yes	Yes, in class, Yes, some	SolidWorks, AutoCAD	Yes, CAD used significantly more than physical models	CAD	CAD
3/24/2021 13:35:50	Yes	Yes, in class	Inventor, AutoCAD	Yes, CAD used slightly more than physical models	physical models	CAD
3/24/2021 14:28:15	Yes	Yes, in class	Inventor, AutoCAD	Yes, CAD used slightly more than physical models	physical models	CAD
3/24/2021 15:12:09	Yes	Yes, in class	SolidWorks	No, CAD used significantly less than physical models	physical models	physical models
3/24/2021 16:34:12	Yes	Yes, in class, Yes, for a job	SolidWorks, Inventor, AutoCAD	Yes, CAD used significantly more than physical models	CAD	CAD
3/24/2021 17:15:53	Yes	Yes, for a job	SolidWorks, Inventor	No, CAD used slightly less than physical models	physical models	CAD
3/25/2021 17:01:48	Yes	Yes, in class	Inventor	Yes, CAD used slightly more than physical models	physical models	CAD
3/28/2021 20:51:24	Yes	Yes, in class, Yes, for a job	SolidWorks, Inventor, AutoCAD	Yes, CAD used significantly more than physical models	CAD	CAD
4/4/2021 11:43:43	Yes	Yes, in class, Yes, for a job	SolidWorks, Inventor, AutoCAD	Yes, CAD used significantly more than physical models	CAD	CAD

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