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Evaluating Computer-Aided Design Software as a Barrier to Women's Engagement in Engineering: A Focused Literature Review

Elizabeth DaMaren

Elizabeth DaMaren is a Master's of Applied Science student at the University of Toronto in Industrial Engineering with the Ready Lab. Her research focuses on team dynamics and gender considerations in Computer-Aided Design (CAD) software education. She previously worked as Project Coordinator for the Engineering Collaboration for Online and Remote Education (E-CORE/CIEL Project), a national Canadian initiative to support instructors in shifting to remote instruction during the COVID-19 pandemic.

Alison Olechowski

Alison Olechowski is an Assistant Professor in the Department of Mechanical & Industrial Engineering and the Troost Institute for Leadership Education in Engineering (Troost ILead). She completed her PhD at the Massachusetts Institute of Technology (MIT) studying product development decision-making during complex industry projects. Dr. Olechowski completed her BSc (Engineering) at Queen's University and her MS at MIT, both in Mechanical Engineering. Dr. Olechowski studies the processes and tools that teams of engineers use in industry as they design innovative new products.

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Abstract

To tackle today's toughest problems, like climate change and the threat of global pandemics, design teams will need to deliver not only software solutions, but also innovative hardware products, sometimes called "tough-tech" or "hard-tech." Computer-Aided Design (CAD) is a key tool for these design teams to leverage in order to reach creative, innovative, hard-tech solutions for society's most pressing issues. Given CAD's importance in design, it is positioned to be a key enabler, or barrier, to increasing diversity in design teams. Statistics on the representation of women in CAD-reliant engineering fields, such as mechanical engineering, show that the numbers remain much below the overall female representation in engineering, and far below gender parity. Differences in confidence and ability level with CAD software are factors that may explain why this disparity exists, and so a focus on increasing accessibility of this tool provides an opportunity to increase female and non-binary representation in design teams.

In this paper, we conduct a focused literature review to provide a comprehensive understanding of what factors position CAD as a barrier to women's engagement in engineering. The primary finding of this literature review is, in fact, the lack of literature; a deep body of knowledge exists to understand Women in Engineering and gender barriers in the profession more broadly, and in parallel, a rich literature on considerations for designing effective and efficient CAD tools and training exists. Yet we see a distinct lack of literature with a primary focus on the intersection of gender considerations in CAD. Based on the limited literature we did discover, we identify several potential barriers to gender diversity in CAD-reliant engineering fields: gender bias in CAD training, lack of representation of women in CAD communities, gender disparity in spatial reasoning skills, and differences in self-efficacy levels. With knowledge of these barriers, we then propose two strategic approaches for leveraging CAD as an avenue to increase gender diversity in mechanical design, which incorporate course design, outreach activities, and general considerations for engineering. These preliminary recommendations can be utilized by educators to support women and non-binary students towards the goal of creating more diverse design teams in undergraduate studies and beyond, ultimately leading to the innovative and creative hard-tech solutions needed to solve society's biggest problems. Importantly, we aim for this paper to act as a motivator to conduct further research in the area of gender considerations in CAD tools and trainings to better understand the actual barriers that women and non-binary individuals face in this field.

Introduction

Engineers will need to play a critical role in addressing the increasingly complex challenges of the world. Many engineering associations, including Engineering Deans Canada [1] and the National Academy of Engineering [2], have published lists of engineering 'grand challenges' to outline these complex issues that society faces. These problems span the fields of medicine, clean energy, infrastructure, and more; all will require innovative engineering design solutions to tackle. More recently, we have seen how engineering and manufacturing play a crucial role in the rapid response to the threat of global pandemics [3]. In addition to entrepreneurial software solutions, we will need to develop and validate hardware products, sometimes called "tough-tech" or "hard-tech" solutions. A key tool required by the teams designing these increasingly needed hardware solutions is computer-aided design (CAD).

CAD software, as with most software systems, has evolved in recent years into a more agile, innovative tool which provides designers with more freedom in their work. Today, CAD plays a crucial role in the design and manufacturing of nearly all physical products. CAD has also been shown to aid in the design process by facilitating design thinking and enabling designers to rapidly explore design alternatives in a rapid, iterative fashion [4]. CAD's importance in manufacturing and the design process positions it as a key tool for design teams to reach creative, innovative hard-tech solutions to society's most pressing issues. CAD's importance also positions it as a key enabler, or barrier, to increasing diversity in design teams.

Research on teams has shown that diversity, including gender diversity, leads to an increase in the quality of work by improving collective intelligence of groups, encouraging equitable contributions in team settings, and adding new perspectives to groups [5]. Gender diversity, specifically within engineering, has been investigated for many years, as it is widely accepted that the representation of women in engineering needs to be increased. This is reflected in efforts such as Engineers Canada's 30 by 30 initiative, which directly targets this goal by working with regulators, higher-education institutions, and other key stakeholders to increase the percentage of women in engineering [6]. These efforts appear to be working, as reflected by the 26.5% increase in female enrollment in undergraduate-level engineering programs in Canada between 2015 to 2019 [7]. There are, however, discrepancies in this representation across different engineering disciplines. Specifically, the representation of women in CAD-reliant engineering fields, such as mechanical engineering, remains low; not only below gender parity, but also below that of engineering more generally. This gap is illustrated with recent statistics; for example, in 2015, a review was conducted of authors publishing in the American Society for Mechanical Engineers and found that of the approximately 100,000 authors publishing in mechanical engineering disciplines, only 15.6% of them were women [8]. According to the National Science Foundation, women accounted for only approximately 14% of mechanical engineering degrees awarded in the United States in 2018 [9], with similar numbers being found in Canada [7], [10]. An additional challenge is that most gender demographic reports and information are still presented with the binary gender system, obfuscating any data there may be on the severely limited representation of non-binary and other gender diverse individuals.

The clear lack of gender diversity and representation of women, non-binary, and other gender diverse individuals in CAD-reliant engineering fields leaves us questioning the drivers of this observation: is there something specific to these disciplines that prohibits the improvement of gender representation? In an effort to advance the understanding of this question, we were interested in investigating CAD tools specifically. Given CAD's prevalence and near ubiquitous use in mechanical design and related disciplines, we believed that the accessibility and barriers surrounding this software could be a key explaining factor as to why the gender disparity exists. As such, in this paper we conduct a focused literature review on CAD and its accessibility as it pertains to being a barrier, or enabler, to women and gender diverse individuals in CAD-reliant engineering disciplines. Note that while this paper's objective it to look at gender considerations and thus uses gender terms such as women and men, some of the literature found and discussed used sex as the demographic identifier, and in those cases female and male will be used to properly represent the findings. We begin by outlining our methods of conducting the focused literature review, followed by a presentation of literature found, which we then sort into two strategic frameworks to address gender diversity. We conclude with our limitations, a summary of the key takeaways of this focused literature review, and areas of future work.

Method

A focused literature review was conducted to provide a comprehensive understanding of what factors position CAD as a barrier or enabler to female, non-binary, and gender diverse engagement in engineering. To begin, search strings consisting of a combination of terms representing *women/gender*, *computer-aided design*, and *barriers* was used in a number of high-impact mechanical engineering design publications to search for literature within mechanical engineering research itself. The search term was purposefully kept vague as to find any possible relevant literature in these journals. The list of journals searched included the ASME Journal of Mechanical Design, Research in Engineering Design, Design Studies, Computer-Aided Design, and Computer Aided Design & Applications. In addition to the initial search in these journals, a search with a similar query was conducted using Google Scholar to begin searching for literature outside of mechanical engineering design specifically.

After this broad search of the literature, the initial collection of papers was reduced based on a set of exclusionary criteria. Some papers were discarded due to irrelevancy; as was expected, the broad search term included a number of papers which focused on topics outside the scope of this review (e.g. challenges in using CAD to design garments for women). Papers were also excluded where the focus was on women as the clients of products, as we were in search of CAD as a barrier for designers. With these exclusions, the initial set of papers used for a preliminary analysis was 64 papers. These were analyzed and sorted, and we distilled four main themes of challenges: spatial reasoning, self-efficacy, mentorship/representation, and gendering of field. A second round of literature searching was then conducted via databases such as Google Scholar and Science Direct, this time including additional search terms to narrow results. In this search, papers related to the four main themes, but not necessarily CAD itself (e.g. papers on self-efficacy in engineering more broadly), were also collected to provide further insight into these issues more broadly in the hopes of then being able to apply them to the specific topic of study. This second search resulted in an increase to a total number of 86 papers to be analyzed. During the second round of searching, three additional themes relating to CAD as an enabler were also distilled: course design, outreach efforts, and general engineering considerations.

A substantial finding of this work -- even before the papers were analyzed -- was the lack of literature directly relevant to the topic of study despite the widespread popularity of CAD in mechanical engineering education and industry. First, there was an overall lack of papers which directly studied gender barriers and considerations with CAD software and training. Second, many papers that were found with the search query of *women/gender*, *challenges*, and *CAD* did reference learning strategies and challenges users face with the tool, but did not break down their findings by gender specifically (e.g. they reported a certain number of women participants, but did not disaggregate their findings based on gender; see [11] for an example). Some of these instances are reported below, as the results could still be applicable to investigating gender barriers in CAD; however, this lack of disaggregated data does reduce the capacity to directly understand the implications of the study for gender. Additionally, papers would often mention CAD software as an example, or as a tool to be used, but focused on the design process more generally without specific considerations for CAD. Again, these papers were still included, as findings can be related back to CAD within the framing of this literature review.

We analyzed our collection of 86 papers after the second round of literature searching to distill findings relevant to the topic of CAD as a barrier/enabler for women in engineering. This distillation and analysis resulted in a total of 59 papers which were found to be applicable to the goals of this focused literature review. We present the key findings from these papers below.

Positionality statements

The positionality of researchers can influence their work at various stages throughout their study, including the research topic, epistemology, and methodology [12]. There are growing calls to include positionality statements in research to increase accountability and improve understanding of the context of work conducted (e.g. [12], [13]). As this research pertains to gender diversity in engineering, below we present individual positionality statements to elucidate our stances on equity, diversity, and inclusion considerations relevant to this work.

DaMaren – I am a white, cis-gender woman with a technical engineering background, including a post-secondary education in engineering and some time in industry. I firmly believe in the importance of supporting women in engineering and women in STEM more broadly, as well as the need for broader gender representation in these fields. As the primary author, I acknowledge that my viewpoint as a white woman with an engineering background influenced the analysis conducted here, and the conclusions drawn from the literature review are my own interpretation of the data as seen through my viewpoint.

Olechowski **-** I am an educated white woman with the privilege of credibility attained from my education, employment track record, and identity. I feel that engineering suffers from an imagined "rationality" [14], which exacerbates societal bias and equity, diversity and inclusion challenges. I have an interest in intersecting my research in CAD with my interest in EDI, and therefore was motivated to fund and supervise this work.

Results

The limited literature pertaining to our topic of interest reveals four main perspectives of CAD as a barrier to gender diversity in engineering: 1) gender bias in CAD training and the mechanical engineering discipline more broadly; 2) a lack of representation of and community for women in CAD and CAD-reliant engineering disciplines; 3) existing gender disparity in spatial reasoning skills; and 4) lower levels of self-efficacy of individuals. We further uncover three main areas in which CAD could act an enabler to increasing gender diversity in mechanical engineering and other CAD-reliant engineering fields. These areas of findings are summarized in Fig. 1.

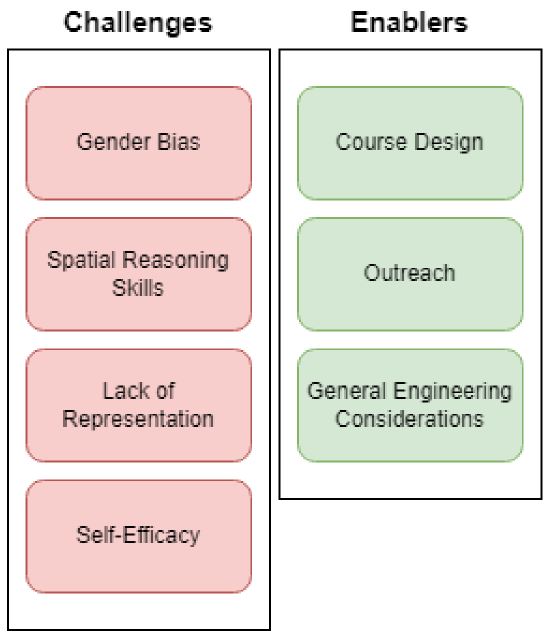

Fig. 1: Areas of findings from lit review

Gender Bias in CAD and Mechanical Engineering

Historically, computers and technology have been seen as gendered, masculine disciplines in society [15]. In the '90s, research showed that males were more computer-oriented in general than females, which was largely attributed to socialization and gender roles at the time (e.g. males being technical and females being artistic and "less concerned with practical issues") [16]. This bias towards males being more technical and computer-oriented shows from an early age in children, where girls have been found to prefer computer programs that emphasize communication and inter-personal skills [17]. Though these studies were not directly focused on CAD software, they do provide insight into how, in general, societal standards and socialization of individuals based on gender has the potential to pre-dispose an individual towards or away from technical software like CAD tools.

Looking more specifically at CAD itself, research shows that gendering and gender stereotypes of the examples and projects used in CAD training can have an influence on recruitment and success of women. A study published by Günay et al. investigated the effects of gender orientation, amongst other factors, on student performance in projects which included the use of computer-aided drafting drawings [18]. They found that when the project topic was skewed towards a certain gender, the average expected student performance fell relative to those students working on more gender-neutral projects. Okudan & Mohammed in 2006 studied first-year engineering students in an introductory engineering course, and also found that a gender bias in the project dominant gender orientation may have an impact on retention rates of women [19]. Similar trends in the need to avoid overly gendering CAD projects can also be seen in outreach efforts. For example, the 'Einstein Workshop' in Boston is a makerspace-like area where children are invited to play with STEM-related tools and kits. In their CAD course, they have labelled the project as "Model Home" rather than "Doll House" to attract a more gender diverse group of participants [20].

Though not CAD-specific, the literature search also reveals interesting findings regarding the gender bias in mechanical engineering specifically. It is widely regarded that engineering as a discipline is male-dominated and has a gender bias towards male and masculinity. A 2018 study found that women perceived engineering as more gender biased than men, and more generally that this perceived bias was the dominant predictor of gender diversity across college majors (i.e. those majors with more embedded gender bias had a smaller representation of women) [21]. This highlights how gender bias in a field is importantly related to gender diversity in that field, which may provide insight into why mechanical engineering suffers a lower representation of women compared to some other engineering disciplines. Gilbert conducted a study at a technical university in Switzerland investigating the differences in culture between materials and mechanical engineering [22]. She found that mechanical engineering had a heavier male gender bias than materials engineering; materials engineering had a more open culture which promoted diversity and the de-gendering of the field, while mechanical engineering had more of a group culture which contributed to male dominance in the discipline.

Lack of Current Representation & Community

In the introduction section, we presented a variety of statistics indicating the low representation numbers of women in CAD-reliant engineering disciplines, both in educational institutions and beyond [7]–[9]. From these numbers, we can see that the representation of women in specifically mechanical engineering, a field that heavily relies on CAD software, lies around 15-20%. These reports did not comment on non-binary or other gender-diverse individuals, so there is a lack of data on what representation looks like outside of the gender binary; however, it is not unreasonable to assume that, due to their lack of inclusion in these types of reports, their representation numbers are far below that of women. This lack of gender diversity in the general population of those in CAD-reliant engineering fields would suggest the probable lack of women and non-binary mentors and leaders in these disciplines.

This lack of gender diversity can be viewed through the lens of critical mass theory, as first presented by Kanter in 1977 [23]. This theory proposes that there is a critical mass, or ‘tipping point’, to representation of women and minorities which, once met, can allow for that group to influence and shift the culture of the whole group. This theory has been demonstrated more recently, for example by Centola et al. in 2018, where the tipping point was shown to initiate social change dynamics and overturn previously established behaviour in a population [24]. The exact percent representation of the critical mass has not been proven, but it has been hypothesized to be between 20-30% [24]; a number above the representation of women in mechanical engineering fields. Though we do not have exact numbers on the women in CAD communities, the representation in mechanical engineering would indicate that it is also below this critical mass point. If we were to hit this critical point, women could start to enact change in these communities to overcome the previously discussed gender bias.

Gender Disparity in Spatial Reasoning Skills

Perhaps most relevant to the topic of gender considerations in CAD is the body of literature on spatial reasoning skills as they relate to CAD and engineering more generally. Spatial reasoning skills have been dubbed a potential ‘gateway’ into engineering [25] due to their importance in the engineering discipline. They have been shown to provide students with a more diverse repertoire of approaches to problem solving [26]. However, the importance of spatial reasoning skills in CAD and engineering is not universal in the literature; some data suggests there is little correlation between these skills and ability with CAD (e.g. [27]). Other studies, such as Hamlin et al., have indeed found a connection between spatial reasoning skills and one's ability with CAD software [28], and so these skills stand to act as a barrier to CAD software.

There is an abundance of literature, particularly in the field of psychology, pointing to the difference in spatial skills between men and women. A meta-analysis conducted in 2019 by Lauer et al. of over 300 studies revealed a distinct difference in the levels of spatial reasoning skills between men and women, particularly in mental rotation performance [29]. An investigation conducted by Dawson into spatial abilities as they relate specifically to STEM again showed a difference in spatial skills between men and women; he claimed that while spatial reasoning skills were positioned as an initial barrier into STEM and retention, and can attributed to factors such as socialization in early childhood, the difference may in fact be lessening over time [25]. A 2019 study by Budinoff, Ford, and McMains found that there was a statistically significant difference in spatial reasoning skills between males and females in an introductory engineering graphics course which utilized CAD software [30]. They also found that on average, females performed worse in the course overall than males; however, the difference in spatial reasoning ability was not fully able to explain the discrepancy in grades, indicating that other factors must be influencing the gender gap in performance. Furthermore, the difference in spatial reasoning skills may not be as important as most literature suggests for women using CAD software. A 2012 study conducted by Winn & Banks analyzing a CAD course for teenagers found no difference in the improvements between male and female students, and no impact of spatial reasoning skills on performance [31]. They noted that instructor confidence in the course and student attitude towards the work were more substantial factors in predicting performance, suggesting that spatial reasoning may be less of a barrier for CAD use than it appears.

Though there is no clear answer as to the exact level of importance and influence of spatial reasoning skills on use of CAD software between genders, they may be one of the 'gateways' into engineering [25]. Training in spatial skills has also been shown to increase overall confidence in engineering, especially pertaining to women [26], and so it is important to look at ways to lower this potential barrier and invite more diverse participation in CAD-reliant engineering fields. There are a variety of techniques found to increase spatial reasoning skills in the literature. Sketching and modelling practice have both been found to address this barrier [25], [32], and introductory engineering courses themselves that include sketching and modelling have shown to improve spatial skills [33]. In addition to sketching, origami folding has been shown to improve these skills [34], as well as incorporating physical artefacts via 3D printing in CAD learning to help build 3D spatial awareness [35]. There is a host of literature on improving spatial visualization skills through various targeted training [36], [37], providing a wide variety of methods to overcome this potential barrier to using CAD for women.

Self-Efficacy of Individuals

Self-efficacy can be defined as the belief in one's ability to execute behaviours and exercise control over their actions [38]. According to a 2009 study by Marra et al., self-efficacy of women has been linked to their retention in engineering more broadly, and has also shown to decrease over time [39]. Similar findings have been found in other studies of engineering students [40] and women in STEM more broadly [41]. A 2020 study by Hilton et al. which investigated makerspaces at three schools revealed that female users had lower expectations of success and high anxiety in using the equipment [42]. This was in part attributed to the lack of female representation in makerspaces. Low self-efficacy was also found to negatively impact spatial reasoning skills [43], making a direct connection to CAD and presenting self-efficacy as a potential way of improving gender diversity with this software. However, as with many of the findings from this literature review, there is also evidence that does not find self-efficacy to be significantly different between genders. A 2010 study surveying over 700 undergraduate engineering students found that there was overall no difference in self-efficacy ratings of male and female participants [44]. This study, however, was not broken down by engineering discipline, and it did find a difference in self-efficacy between genders when it looked at coping self-efficacy, or the ability to cope with failure and challenges. The study did note that the lower levels of coping self-efficacy could be a factor in the retention of women in engineering [44], thus indicating some support for the prevailing literature that self-efficacy is important to consider in attracting and retaining women into engineering disciplines.

In addition to outlining the importance of self-efficacy, the literature review also reveals several ways to increase self-efficacy in women. Participating in engineering courses containing CAD work and receiving training on the software has shown to increase self-efficacy in confidence using the software [45]. Outreach programs have shown to improve self-esteem as well [46], [47]. A study by Delahanty & Silverman found that having strong mentors was an important factor in improving creative self-efficacy [48], and mentorship has been shown to be important to the retention of women more broadly [49], [50]. Additionally, targeted training in spatial reasoning and strategy has been found to contribute to self-confidence in engineering, especially for women [26], positioning this training to potentially improve both spatial reasoning skills and self-efficacy at once.

Area of Improvement: Course Design

The literature search reveals three areas in which CAD tools could be utilized in the promotion of women and gender diversity in engineering, thus positioning CAD as an enabler, rather than a barrier. The first is via course design. Courses using CAD and project-based learning (PBL) have been shown to improve performance of students, and the collaborative learning approaches afforded by PBL seem to increase the success of female students [51]. The flipped classroom approach of providing remote learning modules -- allowing for more hands-on, direct learning in the classroom -- has also shown to improve learning outcomes related to CAD curriculum [52], though not specifically for women. Similarly, blended learning and ‘reusable learning objects’ can improve student learning behaviour in CAD, along with student engagement and knowledge retention [53]. Gamification of engineering has also been shown to be a potential tool to improve the motivation of female students [54]. Further, improving the quality of the course in general has shown to be effective in improving learning in CAD classes, such as encouraging higher attendance rates in students and minimizing distractions in classroom environments [55]. Novel training techniques for CAD software, such as learning from errors and negative knowledge development as described by Mandorli & Otto [56], also promise improved CAD training, though again not specifically targeted towards women.

There is some literature which does point towards course design and considerations specifically for women and CAD. In a 1999 study, Oritz conducted a follow-up survey for women who had participated in a course dedicated to women over the age of 30 to teach them skills in CAD and to introduce them to mechanical engineering technology more generally [57]. The study found that, while none of the surveyed participants had ended up pursuing a career in mechanical engineering or CAD, the course had improved their confidence with CAD and computers, and they reported that these benefits carried over into the careers the women had pursued. More recently, Tannebaum & Simmons investigated women using 3D printing, and using CAD to create the designs to be printed. They found that with 3D printing in makerspaces, women preferred to work in teams, overall visited the spaces less frequently than their male colleagues, and were less comfortable in the spaces [58]. This outcome can be attributed to several factors, including the women's limited previous exposure to this type of technology in high school, and the women being less involved in technical extracurriculars when compared to the men. The authors succinctly explain that "all users enter a makerspace and see the same 3D printers and tools, but access and methods of supporting users may vary, thereby affecting students' experience in these spaces" [58]. This indicates an opportunity to improve access and support to increase gender diversity in these spaces. Other literature points to methods of studying student experience and emotion when using CAD for design, such as Villanueva et al.'s 2018 multimodal study on emotions and electrodermal activity in design activities [59], which could have applications for finding ways of making CAD software more accessible. Similarly, Zhou et al. [60], Phadnis et al. [61], and Deng et al.'s [62] studies point to multi-user CAD as a new technology with the potential for higher user engagement, collaboration, and learning. Unfortunately, these studies, even when they report participant gender, are limited by a lack of gender analysis, thus failing to report on how women may experience these differently than men.

Area of Improvement: Outreach

Outside of dedicated classroom activities and spaces, outreach events and efforts leveraging CAD can also play a role in bringing more women in CAD-reliant engineering fields. This can start early in a person's life; Einstein's Workshop in Boston, for example, provides a space for kids to play with STEM-related technologies, including CAD and Legos [20]. While this space provides an early pathway into STEM for children, they have reported challenges attracting young girls to their more technical space. Looking at older students, there is considerable literature detailing CAD outreach events to high-school aged students. Programs can be designed to create a 'pipeline' for high school students into engineering and STEM disciplines. For example, the Environmental and Spatial Technology (EAST) program is a high school course found in Hawaii and other US states that provides female students with connections to business, industry, and government, and includes teaching on a number of technologies, including CAD [63]. Bahadir [64] outlines a variety of outreach programs run for K-12 students at Southeastern Louisiana University to increase student interest in engineering using CAD and 3D printing. Some outreach programs that are currently successful in generating interest in CAD and engineering have begun to address the need to increase women and other minoritized groups' involvement. For example, the West Point Bridge Design Contest for middle- and high-school students, a national US remote bridge design contest, has shown to be a successful engineering outreach program, but has suffered from low representation of minority participants, which they've indicated a need to improve on [65]. Other programs specifically target women; for example, Horton [66] details a "Girl-Friendly" CAD camp. The camp only had 25% female participation, but it emphasized female mentors and instructors to "normalize" female participation in CAD and the technical discipline. Though some years ago, the "Access To Careers In Engineering" outreach program targeted recruitment of women into engineering and contained a mechanical engineering technology lab as a component of the program [46]. The session as a whole was reported to increase participant knowledge about engineering technology, improve participant self-esteem, and encourage the participants to pursue engineering. Though not all of these outreach programs from the literature are contemporary, they all hold important lessons and considerations for running outreach program for women and CAD technology.

Area of Improvement: General Engineering

Beyond specific course designs and outreach programs, the literature reveals some general considerations for increasing accessibility of engineering and CAD technology for women. Osta et al. in 2020 studied the main factors influencing the retention of women in engineering, and found that supportive family and friends, mentorship, coursework, career goals, internships and research opportunities, pre-college engineering experience, and support professors/staff were found to be the main factors [50]. Amelink & Meszaros in 2011 also found that faculty interaction in the classroom, particularly receiving feedback and being treated with respect, was an important consideration in retention of females in engineering [49]. Looking outside of mechanical engineering, findings of International Women in Medical Physics and Biomedical Engineering Task Group in 2020 on achieving gender balance found that role models and mentoring, dedicated career guidance, and support programs were important in attracting and retaining women to their discipline [67]. From this literature, important lessons can be learned in the application of CAD as a recruitment and retainment tool for women in engineering.

Lack of literature

The literature search revealed a number of interesting factors influencing CAD's position as an enabler to diversity in engineering, reviewed in the Results section above. However, perhaps the most significant result of this literature review is not the factors found, but rather the overall lack of literature applying a gender lens to CAD. Some, such as Piegl, have identified the lack of research in CAD based on gender and human factors, including a lack of information about the potential differences in how men and women design using CAD [68]. It was not uncommon in the papers found in this literature review to mention the gender demographics of the participants, but then to not report the results in a disaggregated way, which could be helpful in identifying further considerations for increasing representation of women, non-binary, and gender-diverse individuals in CAD. Additionally, when compared with similar fields of research in the participation of women in engineering (e.g. that of coding as an enabler to women software engineering – see [69]–[74] for examples), the lack of literature and research on CAD as an enabler for women and nonbinary individuals is indicative itself of the current state of the discipline. Given the importance of this tool and its ubiquitous use in design engineering, and the issues still faced regarding achieving diverse and equitable gender representation in engineering, this is a topic that could provide key information for advancement of women, non-binary, and gender diverse representation in engineering.

Discussion

The above section captured the main findings from the literature review. Overall, a primary finding is the lack of dedicated literature with gender considerations in CAD, therefore motivating the need to invest more in this type of research to deepen our understanding of the phenomenon and investigate how we might better design CAD tools and training for gender diversity. In spite of this lack of literature, in this discussion section, we draw connections between the limited learnings from the literature and synthesize key considerations for educators and engineering professionals in how we may take further steps towards achieving gender diversity and equity in CAD learning and CAD-reliant engineering fields. Note that due to the lack of literature surrounding non-binary and gender diverse individuals, this discussion focuses on the inclusion of women, and while we hope that these recommendations could be adapted for gender diversity more broadly, we are reluctant to make recommendations not based in literature found.

We have taken the four areas of challenges and the three areas of enablers and restructured the learnings into two strategic approaches, which we describe below along with providing suggestions on how these strategic approaches can be implemented in a practical way [Fig. 2]. While these challenges and enablers are not mutually exclusive, and elements of each can be seen in both strategic approaches, we believe the strategic approaches nonetheless provide a helpful method of interpreting and applying the learnings here.

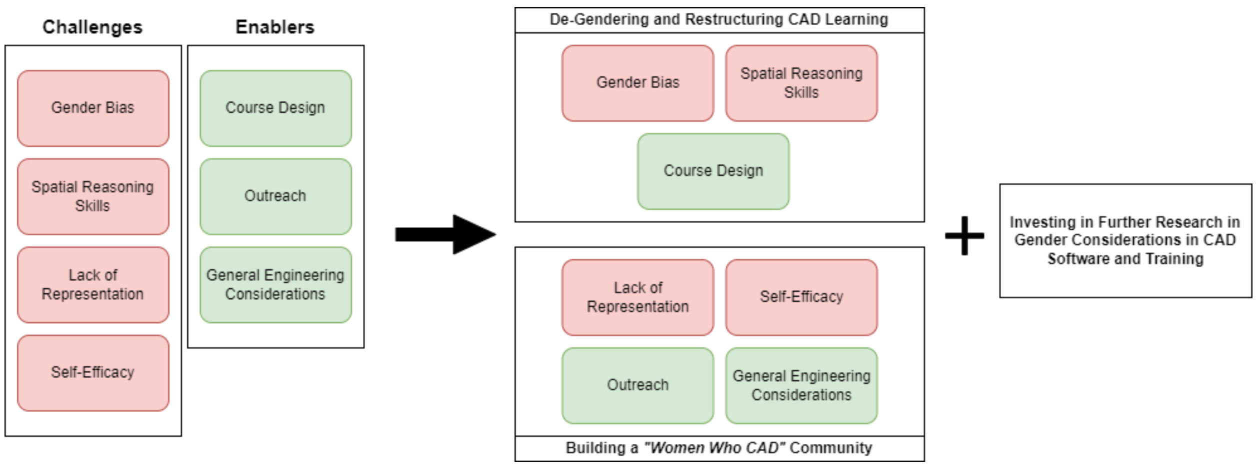

Fig. 2: Two strategic approaches developed to structure learnings from literature review

De-Gendering and Restructuring CAD Learning

The first strategic approach reimagines CAD learning in a way that addresses gender biases and possible gender disparity in spatial reasoning skills by rethinking our course and classroom designs. As seen from the literature review, gender bias within the project topics used in CAD learning can have an impact on the recruitment and success of women in learning [18], [20], and mechanical engineering more broadly has been shown to have a culture of male dominance [22]. Additionally, though not universally agreed upon, there is evidence suggesting that there may be disparities between genders when it comes to spatial reasoning skills [25], [29], which are important in CAD learning and success in engineering more broadly [25], [26], [28], and which can be reduced or eliminated altogether with targeted training [25], [32]–[37]. Both concerns can be addressed, at least in part, with proper considerations into course design for CAD learning.

There are several specific actions that can be taken to de-gender and restructure CAD learning. We can begin by looking at the structure of the learning more generally. As was found in the literature review, we can implement teaching methods in CAD learning environments that have been shown to improve inclusivity and student learning; this includes methods such as project-based learning [51], flipped classroom approaches [75], and gamification [54], amongst others. An important caveat here though is that these techniques will need to be re-evaluated in a post-COVID-19 learning environment as we incorporate new methods of hybrid learning into our education systems. Perhaps less drastic than restructuring entire courses is the technique of reconsidering CAD project topics to ensure they are not skewed towards any particular gender to increase student success [18]. We can also work to provide dedicated support for our women students during CAD training, for example by allowing for more team-based learning during training [58]. Targeted training could also be added for women to address potential areas of improvement, such as in spatial reasoning skills via sketching or origami exercises [32], [34]. Finally, ensuring that there are women included in the training team, as members of the teaching team or via mentor roles, can help to destigmatize and normalize their involvement in CAD software and CAD-reliant engineering fields [66]. This is also strongly linked to the representation of women in CAD, which we build upon in the second strategic approach.

Building a "Women in CAD" Community

The second strategic approach looks to address the challenges of the lack of representation of women and the potential differences in self-efficacy levels between genders by utilizing outreach approaches and considerations for engineering teams more generally. This strategic approach draws inspiration from the community of women in coding, including specific organizations like Women Who Code [76], Girls Who Code [77], and Black Girls Code [78], amongst others. Drawing parallels between these communities and their successes and the existing gaps in the community of women in CAD-reliant engineering disciplines can help to inform potential action alongside the findings of the literature review. The literature review revealed a lack of representation of women in existing CAD engineering fields, as well as evidence that lower levels of self-efficacy can impact the recruitment and retention of women [39]. By building intentional community via outreach and other activities, the barriers can begin to be reduced to encourage more gender diversity.

We see building intentional community via two avenues: outreach methods, and initiatives and activities within already existing engineering communities, be that in educational institutions, workplaces, or otherwise. The literature review uncovers a number of outreach efforts at varying levels, from young children to post-secondary students, both in-person and remotely, which incorporate CAD into their programs [20], [63]–[65]. This may be done by focusing specifically on CAD tools or incorporating CAD tasks as an activity in a larger outreach program. By catering these programs to target women specifically [46], [66], we can promote CAD engineering work and disciplines to women, help improve their self-efficacy and belief that they can be successful with CAD work [43], and encourage them to build support networks early on. Aside from outreach programs, community activities could be implemented in a variety of settings to improve retention and the self-efficacy of women doing CAD work. By forming internal support groups, fostering team learning activities, and encouraging multi-user CAD work, women can be brought together in an intentional fashion to support each other towards the goal of improving retention of women in CAD. Additionally, via these recruitment and retention activities, once a 'tipping point' of the representation of women is reached in CAD communities, we may start to see broader cultural shifts towards inclusivity [23], [24]. Further efforts to build community for women in CAD can draw on the already extensive literature and efforts around women in engineering, including general research on culture change in science and engineering broadly [79], and national efforts such as Engineers Canada's Women in Engineering and 30x30 initiatives [6], [80], as examples.

Limitations & Future Work

Many important considerations have been found through this literature search, but several factors limit the applicability of this study to encompass diversity in engineering more generally. This paper attempted to explore gender diversity more broadly, including women, non-binary, and other gender-diverse individuals. However, a limitation in this search was a lack of literature looking at gender beyond a male/female binary. Only a small handful of papers found mentioned non-binary and other gender-diverse individuals. The distinct lack of literature including considerations of non-binary and other gender-diverse individuals prevented us from drawing conclusions or forming recommendations for those identifying outside of the gender binary. Additionally, while this paper focused on women generally, intersectionality dictates that women of different races, ethnicities, economic statuses, and other demographic identifiers will have significantly different lived experiences [81]. More work needs to be done to identify how women with different identities experience learning and designing with CAD software. Finally, this literature review was not intended to be a systematic literature review, and so it does not claim to be all-encompassing of existing research on gender considerations in CAD. Rather, it was designed to capture the main threads of existing research and draw conclusions and recommendations to be applied in improving the gender diversity of CAD-reliant engineering fields. A future systematic literature review could build on this work in a truly comprehensive fashion to ensure a complete search.

Conclusion

This focused literature review sought to find and summarize the main considerations around computer-aided design software as a key barrier, or enabler, of increasing gender diversity in CAD-reliant engineering fields, such as mechanical engineering. Through two rounds of searching relevant journals and article databases, we identified four sources of barriers to CAD software: gender bias in CAD and mechanical engineering; lack of current representation and community for women; gender disparities in spatial reasoning skills; and self-efficacy of individuals. We also found three areas where different framings and techniques can position CAD to be leveraged to be an enabler to improve gender representation: course design, outreach activities, and general considerations in engineering.

The literature findings were synthesized and brought into two strategic approaches that describe how the results can be integrated into the current state of CAD learning and engineering outreach to improve gender diversity. These strategies of de-gendering and restructuring CAD learning, and building a Women in CAD community, can be utilized by educators and professionals alike to support women and non-binary designers towards the goal of creating more diverse design teams in undergraduate studies and beyond, ultimately leading to more innovative and creative hard-tech solutions to society’s biggest problems.

A major finding of this work was in revealing the lack of literature directly relevant to a gendered analysis of CAD. We have attempted here to construct our strategic approaches based on the literature from related and relevant fields, but as CAD is posed as a critical tool in engineering as engineers tackle increasingly complex research, it will be especially important to dedicate more research to these topics in pursuit of increasing gender and other minoritized group representation in CAD-related engineering fields.

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