Engineering Design Education Research Review

Objective:
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Scoping literature review to analyze the current field of engineering-design education to inform Ignite's 2024 implementation, a human-centered design engineering program for middle school students in Durham, North Carolina. This landscape survey will inform the research study for Ignite's middle-school program with a focus on increasing student self-efficacy scores, tinkering-efficacy, and attitudes towards community-driven problem solving.

Introduction:

The United Nations (UN) General Assembly, a coalition representating 193 different countries, agreed upon 17 goals as a part of their Sustainable Development Goals (SDGs); these interconnected topics span a wide array of issues including climate change, eradicating poverty, health-equity, gender equality, and justice, with the broader mission of promoting 'prosperity while protecting the planet ' [16]. With the increased recognition of such ubiquitous and complex global issues, it necessitates the creation and retention of creative problem-solvers to address these challenges. As a result, it is necessary to implement engineering education programs that employ students with the skillset, confidence, self-efficacy, and motivation to tackle these problems within their own community [14, 15].

The engineering design process is defined by an iterative problem identification, design and problem-solving process that is helpful towards addressing some of our world's largest challenges. Recently the field of engineering education research has been interested in introducing engineering education and design to K-12 students to cultivate the next generation of innovative problem solvers and increase diverse perspectives within the field. However, many under-resourced schools do not have access to STEM-related activities [14, 15, 21]. Thus, many educational initiatives are focused on empowering students from historically under-represented communities to engage in engineering solutions to local issues salient to their communities [4]. For example, many programs have been focused on developing curriculum that focus on decreasing the gender gap [11], improving retention in science, technology, engineering, and mathematics (STEM) [10, 21] , assessing student's self-identity and perception in STEM, and equity-oriented models [4,5]. This literature review evaluated current published literature of innovative engineering models that aim to (1) increase student participation and improve self-perception in STEM; (2) address the racial or gender minority gap in STEM; or (3) encourage a sense of global-citizenship in students in K-12 education. With this analysis, we hope to survey the gaps, challenges, and advances in K-12 engineering education.

Methods

A literature search using the Education Resources Information Center (ERIC) databases, as well as Google Scholar, was conducted, of which 17 studies were included and synthesized. We utilized key search terms such as, 'K-12 Engineering Education Framework,' ' K-12 STEM Education,' 'Girls Stem Education,' 'Stem Education Indicators,' 'young women STEM learning,' and 'engineering education AND equity.' Our review prioritized papers exploring engineering and/or STEM education within our identified student age-group, K-12; although we did include certain undergraduate education sources that we felt were relevant to the structure of our program, such as those that explored self-efficacy. Furthermore, we prioritized engineering and/or STEM education, as opposed to just general education-efficacy articles, as we wanted to focus on the impacts of engineering design education and problem-solving. Additionally, our literature review heavily focused on studies that addressed the racial and/or gender minorities gap in STEM, with an emphasis on utilizing engineering design to address social issues.

EndNote15 was used to manage the selection process, while Google Spreadsheet was used for charting and extraction.

Results

Assessment of STEM Self Efficacy

Across the surveyed papers, many studies discuss the positive links between immersion in STEM education and students' self efficacy in their STEM abilities. In one study, Shang et. al employed the constructivism learning theory and recruited 153 fourth graders from rural areas of China to participate in a three day STEM education study, focusing on developing the students' pre existing skills and knowledge in STEM and problem solving [17]. Through analysis of pre and post surveys, they found that building upon the students' previous knowledge in STEM increased STEM self efficacy, computational thinking skills, and overall STEM abilities. Similarly, George et. al created a camp for 28 sixth grade girls that immersed them in the STEM curriculum [9]. The girls took an assessment test that evaluated the girls' attitudes towards STEM pre- and post- program. These results were compared to the results of girls who did not partake in the STEM camp. This study found that the STEM camp increases math and science self efficacy, but not STEM, engineering, or technology self efficacy; however, this study is limited as it has a short duration, while also creating potentially disparate experiences for the two groups of students.

Apart from immersion in problem-solving related activities, Lu et. al found that online readiness was the factor that affects STEM self efficacy the most [18]. In this study, 851 fifth graders and 535 eighth graders were sampled as they went through STEM curriculum and the results found that a students' ability to use technology as well as their confidence in their ability to use the internet severely impacted STEM performance and STEM self efficacy.

Other studies focused on self-efficacy through a more collaborative lens. Beier et. al utilized collaborative learning theory to determine the effect of group project based learning courses on engineering students' STEM self efficacy and career aspiration [19]. As these students were immersed in the first four semesters of their college STEM coursework, the researchers kept tabs on the students' self efficacy in STEM and their career aspirations. The study found that group project based learning courses played a significant role in self-efficacy as at least one STEM project-based course increased the students' perception of their STEM skills and career aspirations. Additionally, Wilson et al. brings nuance to the analysis of self-efficacy, finding that although there were no correlations between the teachers' and students' STEM self efficacy both groups had an increase of STEM self efficacy by simply being immersed in STEM [20].

Engagement and Retention of Underrepresented Minorities in STEM

Many studies also aimed to increase engagement and retention of students of underrepresented backgrounds or URM students in STEM. Many studies in the past have evaluated career aspirations of high-school students, and one study found that males were 1.9 times more likely to major in STEM, and those with higher science self-efficacy scores are 1.5 times more likely to major in STEM in college. Notably, the study also found that African American and Hispanics were least likely to pursue STEM in college [21] . A study conducted by Tan et. al. analyzed similar trends and utilized a justice-oriented framework focused on equitable and impactful learning to emphasize how these trends of engagement K-12 STEM education are rooted in history and geographies. They also explored the social-spatial relationalities that underrepresented youth contribute to engineering design and how these can empower them to transform oppressive knowledge towards equitable learning. Using data from middle school classrooms, they found that structuring engineering design education around everyday experiences relating to the community helped address and tackle hyperlocal, sociopolitical community issues [4]. Cunningham et. al. also looked into developing a more equitable approach to preK-12 engineering education. They drew from sociocultural theory and established principles of equity to inform instruction, curriculum, and assess preK-12 engineering education programs. They developed a model that focuses on incorporating components such as socially engaged engineering and asset-based pedagogies to help foster students' engineering identity. The different aspects of this model put an emphasis on students' ideas and experiences – which were found to play a significant role in helping them foster an engineering identity [5]. By reaffirming students' engineering identity and allowing students to participate in socially engaged engineering, their model aims to increase students' self efficacy and improve educational experiences, especially for those currently underrepresented in engineering.

Another study emphasized how K-12 STEM education plays a critical role in introducing students to STEM topics and preparing them to enter STEM majors and jobs, but there is less prevalence and opportunities in STEM for students in schools with high-minority and high-poverty enrollment [7]. The model that Kaggwa et. al. developed and implemented through a partnership between racialized minority elementary schools in low income areas and scientists at a non-profit science research institution aimed to tackle this issue. Accessibility and inclusivity were the two main factors that were considered for this model, which directly tie in with creating an equitable approach to engineering education [5, 10]. Through the partnership, they were able to hold five "STEM Days" at the elementary schools to expose students to STEM and stimulate their interests in STEM. After collecting teacher and student responses to a questionnaire and conducting open coding, they found that both students not only were not only able to recall specific STEM facts and information taught during STEM Days, but also were also interested in STEM learning. They also found that it sparked conversations regarding STEM related careers and increased enthusiasm, showing the model's potential for STEM retention and engagement among URM students. Although this program helped address the limited opportunities in STEM for URM students and students in low income areas, a limitation was that it was short-term, since it only lasted for five days.

It has also been found that a slightly greater percentage of female students reported taking a STEM course because someone else had encouraged them to do so, which indicates that having exposure to STEM and creating a supportive environment can further encourage engagement in STEM [7]. This connects to another study previously mentioned above that focused specifically on young girls in STEM, where George et. al. investigated how the implementation of STEM curriculum in a STEM Academy affected middle school girls' self efficacy and attitudes towards STEM. They found that although survey results showed that the program increased self efficacy in math and science, it had little effect in engineering and technology fields. The model that Kijima et. al. created helps to provide insight into tackling this, as they used the constructivist theory to engender creative confidence, empathy, and global competence among female youths (ages 13-18) through a three day design-thinking workshop. Utilizing STEM and STEAM approaches, this workshop aimed to allow young female students to identify and address a real-life problem in a collaborative, social setting, and was found to have built collaboration and communication skills, as well as increase students' creative confidence and interest in engineering [8]. Building upon this, de Melo Berezza et. al. also developed a framework to spark young girls' interest in STEM. However, unlike previously mentioned programs, this program was led by female undergraduate students who were tasked with creating the curriculum and lecture materials to present to the young students. The lectures were also followed by three hour workshop sessions that allowed the students to gain hands-on experience and apply the knowledge that they learned in the lectures. The workshops in particular were found to spark students' interest in STEM and pursuing a STEM-related career, while the lectures sparked interest in STEM related projects. Although structurally similar to the models proposed by Kaggawa et. al. and Berezza et. al., this framework – by allowing female undergrads to lead – helped to engage both the undergrads and students in STEM. Notably, across various programs, they lasted a short duration from a couple of days to only a few weeks.

Data Collection Strategies

Many research studies that focused on applying learning theories in the classroom utilized quantitative and qualitative data collection methods to get a holistic picture of student experience and evaluate program-outcomes. From the studies surveyed, most used interviews, surveys, or a combination of both methods to obtain the data.

Likert Scale

Long et al. posed a direct, close-ended questionnaire to collect data on STEM learning outcomes using the 5-point Likert scale with questions centered around interest, competence, and confidence in STEM before, during, and after a middle school STEM program [1]. Similarly, Bezerra et al. also used a Likert scale to measure student opinions on interest in STEM, importance of STEM, knowledge of careers in STEM, and understanding of women importance in STEM. However, this study used a 4-point Likert scale that omitted the "no preference" option, which may have affected the data since students had to take a firm stance on each question [11].

Interview Data Extraction

Other studies used strictly qualitative methods to collect data. Öztürk et al. conducted interviews with teachers and school principals to gather data on teachers' understanding of STEM education, development of STEM curriculum, implementation of STEM activities, and training on STEM education. The interviews lasted 20-45 minutes, and the interview was either video recorded or recorded through note-taking. The study then used MaxQDA, a qualitative data analysis software, to gain insight on the data [6]. Some engineering design studies combined interviews with survey data, such as Cantrell et. al. which proposed a mixed-methods study utilizing student assessments, design project rubrics, and interview protocols to evaluate middle school students' abilities in knowledge recall, conceptual understanding, and analysis/synthesis. The study incorporated multiple choice, true/false, and short answer questions, rubric grading for the design-project, and oral interviews that were conducted in a one-on-one teacher-student setting [13]. Another study describes how they utilized interviews combined with survey data – similar to what Cantrell et. al. did – with the surveys assessing student confidence and career aspirations regarding science and engineering, along with general understanding of technology and the engineering design process [12].

These studies all used various data collection methods to gain insight into impacts their programs (that were based on specific learning theories) had on students' regarding both general knowledge about engineering and also their self efficacy and attitudes towards it.

Discussion:

Ignite is an engineering curriculum developed by the Center for Global Women's Health Technologies at Duke University aligned with the mission of encouraging creative innovators and problem-solvers to utilize human-centered engineering design to address some of the world's most pressing challenges. Ignite was originally implemented in Guatemala where Duke undergraduate students traveled to teach the engineering curriculum using an evidence-based peer-led co-learning model [15]. Ignite has now been implemented in North Carolina (NC), in collaboration with The Museum of Life and Science with intentions of increasing interest in STEM and STEM retention for young students in NC. The middle school program, pairs undergraduate students, *Trainers,* and middle school mentees, *Learners*, for a semester-long program with three predetermined modules focused on addressing the UN SDGs, Water, Light and Health. Learners are assigned to project groups where they incorporate the prototyping and design skills they learn in the program to create physical prototypes that address their identified problem statement related to one of the UN SDGs [14, 15].

Ignite aligns with many of the current programs and published literature in engineering design education, with goals of increasing self efficacy through situation-determined learning and STEM-immersion. As our surveyed studies noted, increased exposure to STEM and problem-solving activities results in a positive increase in self-efficacy [9]; Ignite addresses this by engaging middle school students to develop interests in problem-solving, and equipping them with prototyping skills. Additionally, Ignite's setting is unique in its collaborative environment where Learners work with other Learners and Trainers, but also fostering independence through creating their own long-term research project based on the identified problem statement they care about. This aligns with Beier et. al's and de Melo Berezza et. al's findings of collaborative learning theory, as it also introduces a collaborative environment for Learners, with other Learners, but also with their undergraduate Trainers [11, 19]. One gap in the current literature when considering Ignite's peer-led, co-learning environment is the mutual-impact of learning and teaching engineering design for the mentee and mentor, respectively; Ignite could fill this gap by analyzing the Trainers' attitudes and aspirations towards STEM after the program, and examine if Trainer and Learner's self-efficacy scores correlate. Furthermore, existing programs have paired younger students with volunteer scientists, but very few have had younger students work with undergraduate mentors like Ignite.

One of the gaps present in the current research is a cohesive cohort of qualitative and quantitative data that represents K-12 student experience in a program focused on engineering education, such as incorporation of both interviews and survey data. While some data on this subject is present, the widespread data collection methods across different studies make simultaneously analyzing results from multiple studies difficult. Ignite's design may be very conducive toward this hybrid quantitative-qualitative data collection method due to the nature of the classroom dynamic and the informal learning taking place, and has potential to optimize upon data extraction through incorporations of the various existing strategies listed in this literature review.

Another gap in the field is there are few programs focused specifically on helping students develop prototyping and tinkering skills. Many of the studies discussed provided students with lectures to gain knowledge about STEM and engineering, but there were very few that offered opportunities for students to gain prototyping experience, especially since the programs only lasted for a few days. Ignite's curriculum aims to address this and allows students to have the opportunity to cultivate their prototyping skills through project based learning throughout one semester; this aims for students to both have high-self efficacy scores, as well as provide them with the tools to solve future problems. This differs from programs that lasted a few days or were shorter in duration, as Ignite-Learners will be able to have sustained exposure, allowing us to also examine how attitudes towards STEM changes throughout the program. Not only that, Learners and Trainers gain tinkering skills that can be applied even after the program ends, following them into their education and potentially career.

Although Ignite shares common goals and objectives with the models developed in the studies, it offers unique features that sets it apart from current programs. As a result, Ignite can address these research gaps and provide students with extended exposure to engineering and prototyping.

Conclusion:

There have been many models and frameworks developed to introduce engineering education and the design thinking process to K-12 students, with the goals of boosting participation and self perception in STEM, addressing the racial gap, and helping to establish a sense of global citizenship among students. Researchers utilized different educational and learning theories to guide in the creation of their framework to help foster students' engineering identity and to allow them to gain experience with identifying and tackling real world issues through workshops. The programs that were implemented, although relatively short in duration, have shown to be beneficial in increasing students' self efficacy and confidence in STEM, as well as spark their interest in STEM and potentially pursuing a related career in the future. Ignite builds upon these models, giving students the opportunity to work on addressing the Light, Water, and Health UN SDGs over a sustained period of time. Additionally, Ignite allows both younger students and undergraduate students to learn and be engaged throughout the program, aiming to boost overall engagement and retention in STEM for both groups. Additionally, Ignite provides students with more exposure to engineering and prototyping, to equip students with both the confidence and tools to continue pursuing STEM. By filling these gaps, Ignite will be able to improve its program in future years and establish a framework that can be reproduced, scaled, and implemented by others.

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