Effects of Engineering Design Process on Science and Mathematics

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***Abstract*—This <u>*work-in-progress research*</u> paper contains the findings from a meta-analysis on the effects of using the engineering design process on K–12 students' science and mathematics achievement. This study uses a meta-analysis methodology to calculate the effect size of the integration of the engineering design process into science and mathematics teaching and learning practices on student's science and math achievements. A sample of empirical studies published during or after 2018 were included, and data were analyzed using STATA 16 statistical software. Analysis revealed a statistically significant effect size (d = 0.31 [*CI*= 0.18,0.44]) on students' science and mathematics achievement. The findings suggest that implementing the engineering design process enhances students' learning experiences and improves their academic achievement in science and mathematics. The results of this WIP meta-analysis should inform instructional leaders and other education stakeholders concerning the importance of integrating the engineering design process into Science, Technology, Engineering, and Mathematics teaching and learning practices.**

Keywords*— *engineering design process, PBL, , STEM

I. Introduction

The engineering design process is a method of constructing solutions in a systematic manner in a wide range of fields, such as product manufacturing, design, research and development, civil planning, and social welfare. The overarching goal of engaging in the engineering design process is to create solutions to any given problem while staying within the boundaries of provided constraints, resources, time, and budget. There are many engineering design process models in the literature (see [1] for a detailed overview of the literature and a comparison of engineering design process models). The engineering design process proposed by [2] integrates project-based learning (PBL) and allows for a more student-centered approach to teaching and learning.

Most engineering design process models have five to seven steps. These steps usually include problem identification, research, ideation, analysis of ideas, build, testing and refinement, and communication and reflection [2]. The engineering design process has been found to be very effective in teaching and learning STEM subjects and has been used as a guide for STEM training of students and teachers [3]. Students find the step-by-step process of problem solving afforded by the engineering design process a great tool [4].

However, the aggregate impact of using the engineering design process to enhance learning in the individual Science, Technology, Engineering, and Mathematics (STEM) disciplines has not been studied (or calculated) to date. In this work-in-progress (WIP) meta-analysis, we calculate and provide an overall effect size of the integration of the engineering design process on students' science and mathematics achievement.

II. Theoretical Framework

Project-based learning allows instructional leaders to integrate real-world hands-on activities into STEM classrooms. This instructional methodology is defined by having a clear goal for the learning tasks with an "ill-defined" process [5]. Research into the efficacy of PBL-driven instruction has shown it can help improve students' academic achievement, motivation, attitudes, and perceptions towards learning STEM coursework [6], [7], [8]. Project-based learning is different from traditional teaching and learning methods because it does not follow the usual teacher- and content-centered approach to learning wherein the teacher is responsible for delivering knowledge through lecture so that students may absorb the information to later regurgitate it on tests. The goal of using PBL activities is to promote student interest in STEM coursework and career fields [5], [9]. Four out of five studies included in this WIP meta-analysis integrated the engineering design process within the PBL framework, demonstrating that it is a suitable pedagogy because engineering problems have a real-life context and often require hands-on approaches to obtain viable solutions and artifacts.

Traditional STEM classrooms often focus on problem solving with a content-centered approach. Project-based learning instruction helps students develop STEM skills and confidence by tackling real-world problems within a learner-centered approach [10]. Recent research has shown that PBL implementation in STEM classrooms has positive effects on students' motivation and self-efficacy [11] while also empowering students to take on additional STEM coursework that may lead to the eventual pursuit of STEM careers. The ccurrent landscape in the U. S. STEM workforce exhibits a lack of diversity. This raises the issue of underrepresentation of certain student groups [12]. Science and mathematics classrooms where the engineering design process is integrated within PBL practices can provide a nurturing environment for all student groups, especially those who have been traditionally underrepresented, by improving their self-efficacy and attitudes towards STEM fields [6]. The research studies included in this WIP meta-analysis confirm the effectiveness of combining the engineering design-based learning process within PBL.

III. SUMMARY OF STUDIES INCLUDED IN THIS META-ANALYSIS

Among the studies (n = 6) selected for analysis, one was a master's thesis [4], another was a research report [13]), and the remaining ones were peer-reviewed journal articles. The studies analyzed in this WIP meta-analysis represent a very small sample of all the literature available on the subject. However, they provide an effective snapshot of how the engineering design process is being integrated into teaching and learning practices and its effect on student achievement. The teaching methods integrated in these studies were the following: a) Direct teaching [3]; b) Next Generation Science Standards (NGSS) oriented practices [4]; c) Learn by Making (LbyM) [13], [14]; d) ADDS [Answer the question, using Data, Details, and Science and engineering vocabulary] used to encourage writing during the engineering design process [15]; and e) Children Using Robotics for Engineering, Science, Technology, and Math (CREST-M) curriculum that was used in innovative learning scenarios by [16]. The interventions in all the studies were focused on science and mathematics achievement, though [3] and [14] employed a further assessment of both science and mathematics achievement.

IV. METHODS

In the current study, the researchers followed a statistical technique called meta-analysis [17], [18]. Through this meta-analytic study, we aim to combine similar quantitative research studies and calculate a cumulative effect size by combining the effect sizes from each individual study. In the current study, the researchers searched for and combined all peer-reviewed quantitative research studies that were published during or after 2018 and which satisfied the inclusion criteria described in a later section.

A. *Research Questions*

The motivation behind this WIP meta-analysis is to explore the answers to the following research questions:

1. What is the effect of integrating engineering design oriented activities on students' science and mathematics achievement?
2. Are there any differences between the above effects on students in elementary, middle and high school grades?

B. *Inclusion Criteria*

The following criteria was used to include potential studies in this meta-analysis:

- English language
- Used engineering design process as a part of the intervention
- Interventions were implemented in K–12 or post-secondary settings with students
- Published in a peer-reviewed journal or conference proceeding or;
- Approved by a committee as a master's thesis or doctoral dissertation
- Published during or after 2018
- Implemented an experimental or quasi-experimental design
- Provided means and standard deviations/standard errors

C. *Literature Search*

The authors conducted a literature search using a two-step search approach using a Google Scholar search for relevant literature using the search query in Figure 1, with the year range defined as 2018 to the present. A list of relevant articles was obtained and the references for those articles were exported to a file in BibTeX format. This file was then imported into RefWorks, an online reference management tool linked to the author's academic institution enabling searches through EBSCO Discover Service. Full-text documents were requested for each reference through RefWorks using EBSCO Discover Service. All available documents were downloaded and saved for coding. In case a document was not available for download, a request was made to the library to locate and convert the document into electronic format. Google Scholar only provides pointers to academic artifacts and is able to cast a much wider net than EBSCO service, but is bound by copyright and licensing issues. 238 articles were selected for further review as shown in Fig. 1. Six studies were chosen for final analysis based on the inclusion criteria and coded using the coding procedure described below.

D. *Coding Procedure*

The authors used a 35-column excel worksheet to code the major characteristics of each study, and they recorded the following: the study number, author, year, quick citation, full citation, publication type, grade level, majority gender, duration in weeks, type of microcontroller, subject area, control sample, control mean, control standard deviation, experiment sample, experiment mean, experiment standard deviation, total sample, Cohen's d, and confidence intervals. This WIP meta-analysis consists of a brief literature review and concerns itself only with a small sample of quantitative studies published during or after 2018.

E. *Statistical Analysis*

STATA 16 [19] was used to conduct a meta-analysis of all studies using the META package and meta esize command with the cohend option to calculate a Cohen's d effect size for each study. The summary of the effect sizes were tabulated using the meta summary command showing all effect sizes along with the 95% confidence interval and % weights for each study. A forest plot of all effect sizes and overall effect sizes were constructed using the meta forest command for a graphical display of the effect sizes.

V. FINDINGS

In this WIP meta-analysis, we analyzed (n = 6) studies containing 18 data sets. The overall effect size of using the engineering design process as an integrated intervention on students' science and math achievement was $d = 0.31(CI = [0.18, .44])$. Based on the signa and the confidence interval, we can conclude that this is a positive and statistically significant effect size. We reject the hypothesis of homogeneity based on the statistically significant Q value of 47.77 ($df = 17$, $p < .001$).

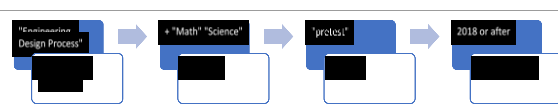

Figure 1. Literature search process

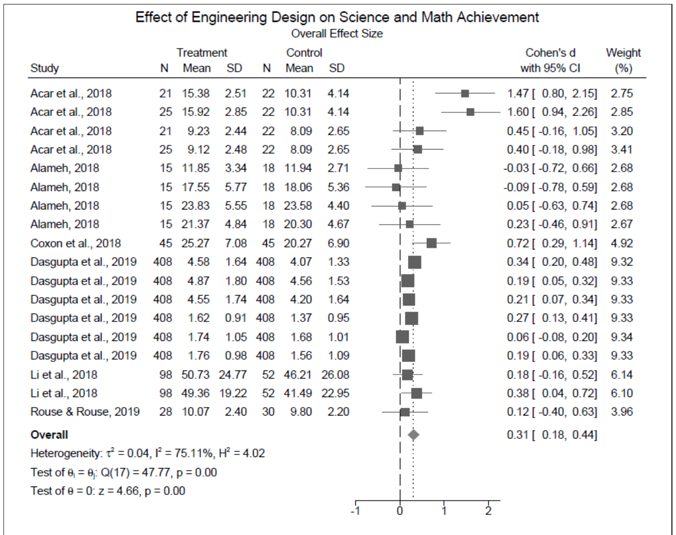

Figure 2. Forest plot of effect size

Fig. 2 shows the forest plot of overall effect size. Fig. 3, 4, and 5 show the forest plot of effect size for the studies that were conducted in elementary, middle and high school settings, respectively. Fig. 6 and 7 show the effect size on science and mathematics subject areas, respectively.

VI. Discussion

In this WIP study, we meta-analyzed 18 data sets from 6 empirical studies in which the engineering design process was integrated into science and mathematics teaching and learning practices. To answer our first research question, we looked at the effects of the integration of the engineering design process on students' science and mathematics achievement. Fig 6. shows

the forest plot of the effect of engineering design integration on student's science achievement. We found that the integration of engineering design had a statistically significant positive effect on students' science achievement (*d* = 0.41 *CI* = [0.09, .73]). Of the 10 effects, three were negative and four were statistically non-significant because their 95% confidence interval subsumed the no-effect value. However, six out of the 10 effects were positive and statistically significant. The findings indicate that the inteventions that utilized STEM training [3], Energy3D CAD software (Dasgupta et al., 2019) [14], and LbyM [13]) curriculum produced statistically significant positive effects on students' science achievement.

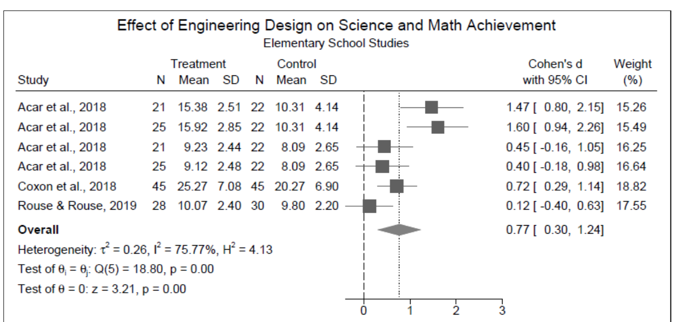

Figure 3. Forest plot of effect size – Elementary schools

Interventions based on NGSS oriented practices [4], however, failed to produce statistically significant positive effects.

The forest plot of effects on students' mathematics achievement is shown in Fig. 7. The results indicate that the engineering design-integrated teaching and learning practices had a statistically significant positive effect on students' mathematics achievements (*d* = 0.23 *CI* = [0.11, .36]). Although the overall effect on students' mathematics achievement was positive, only three out of seven effects were positive and statistically significant. Although STEM traingin [3] has a statistically significant and positive effect on students' science achievement, the effect on students' mathematics achievement was positive with a 95% confidence interval, which subsumed a no-effect value. Crest-M curriculum [16] however had a statistically significant positive effect on students' mathematics achievement. Our findings indicate that engineering design-integrated teaching and learning practices have a positive effect on students' science and mathematics achievements; however, this effect is highly dependent upon the curriculum that is being implemented.

We found differences between the effect on students in elementary, middle, and high school grades. Engineering design-integrated interventions had the most positive effect on students in elementary grades (*d* = 0.77 *CI* = [0.30, 1.24]). The

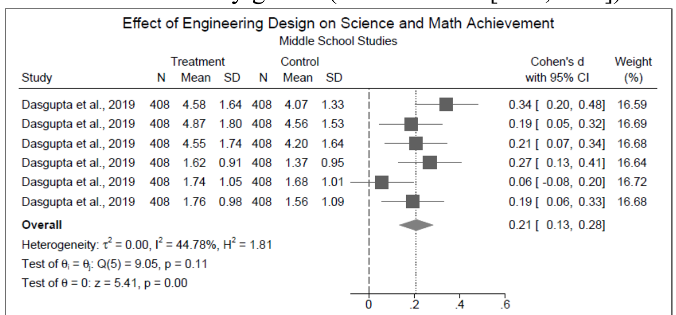

Figure 4. Forest plot of effect size – Middle schools

effect on middle school students ((*d* = 0.21 *CI* = [0.13, .28]) was second in magnitude compared to the effect on high school students (*d* = 0.20 *CI* = [0.01, .40]). Despite the differences in effects at three different grade levels, all three effects were statisitcally significant and positive, indicating that the interventions which integrate the engineering design process in teaching and learning practices helped improve students' academic achievements in STEM classrooms at all grade levels.

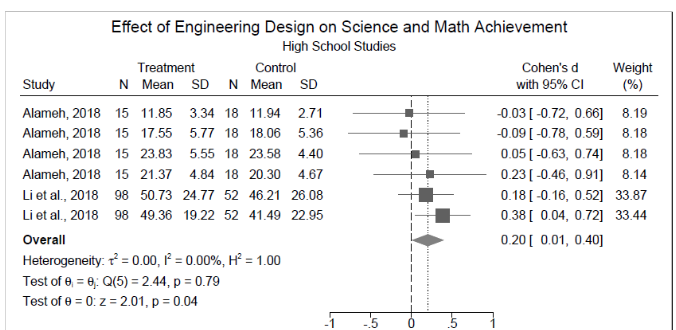

Figure 5. Forest plot of effect size – High schools

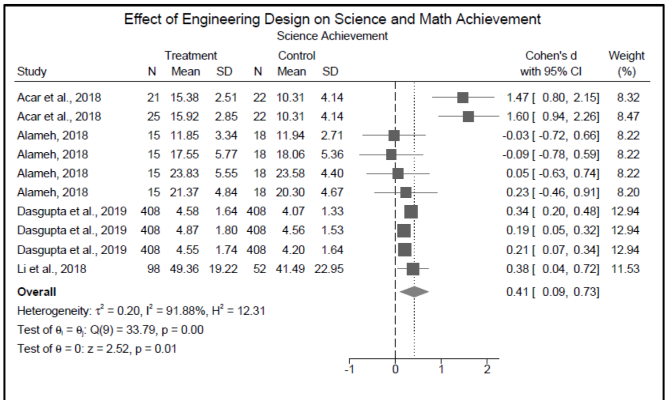

Figure 6. Forest plot of effect size – achievement on Science tests

VII. Conclusion

The empirical evidence analyzed in this WIP meta-analysis from the sampling of published quantitative literature on the integration and effectiveness of the engineering design process into science and mathematics teaching and learning suggests that such integration can have statistically significant positive effects on student achievement. Learning- and learner-based approaches informed the main idea behind the integration of the engineering design process, as they encourage creative thinking and problem solving skills to be applied in science and mathematics classrooms. Engineering design process can be adapted to the needs of the most innovative and state of the art teaching and learning practices (e.g. Internet of Things, microcontrollers and robotics [20], [21].

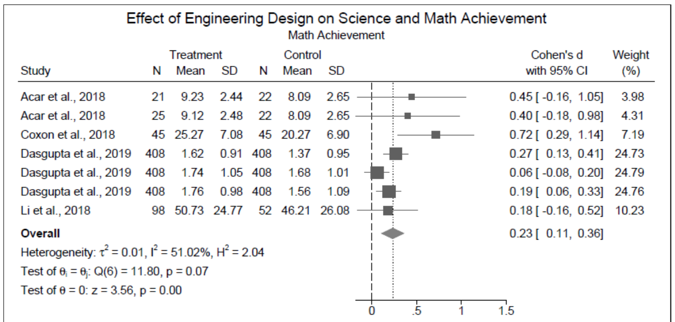

Figure 7. Forest plot of effect size – achievement on Mathematics tests

The positive effects of the use of the engineering design process and PBL teaching and learning practices in STEM classrooms should encourage instructional leaders, STEM educators, and policy makers to adopt and fund these innovative pedagogical methods and make their integration a priority in STEM classroms from K–12 through post-secondary.

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