AC 2011-227: ELEMENTARY ENGINEERING IMPLEMENTATION AND STUDENT LEARNING OUTCOMES

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Engineering Design Models in Elementary Grades

Abstract

K-12 schools across the nation are implementing or considering various curricula that use engineering. From high school curricula that are fairly comprehensive (eg. Project Lead the Way) to textbooks intended for middle or high school courses (e.g. Survey of Engineering from Great Lakes Press) to elementary school afterschool clubs based on activities from engineering societies and more comprehensive sets of activities (e.g. Engineering is Elementary from the Museum of Science, Boston), enthusiam for engineering in K-12 is increasing. These curricular activities' foci include increasing technological literacy and encouraging students to pursue engineering. Although those who are engineers are enthusiatic about this trend, to date, there is only cursory assessment data available to indicate the efficacy of any of these approaches to meeting their respective goals. Consequently, there is no guarantee that the overall effect on the fields of engineering will be positive, if these activities become nothing more than an educational "fad." Solid research on the ability of engineering curricula to support solid student learning is needed. This manuscript describes a project designed to comprehensively assess student learning with an elementary school curriculum (Engineering is Elementary) and a comprehensive implementation in math, science, language arts, social studies and technological literacy. North Carolina State University Colleges of Engineering and Education have partnered with two North Carolina public elementary schools and the Museum of Science, Boston to support existing implementations of engineering magnet elementary schools. The pilot test implementation at an initial test site has been researched with regards to student learning in design, engineering, and science; student attitudes toward STEM content; and teacher implementation and effectiveness.

Introduction

The 2004 National Academy of Engineering study report, *The Engineer of 2020: Visions of Engineering in the New Century*, identifies that based on societal progressions, rapidly improving technological capabilities, and global linkages, that engineering creating a unified and distinct vision for the profession's future and assisting in transforming education to support this vision are clear primary initiatives[1]. A distinct vision and a K-12 educational support structure is above all important in such a transitional age of technology and engineering innovation. K-12 engineering education has the potential to boost technological literacy, more specifically the ability to understand and appreciate the costs, trade-offs, and benefits concerned in determinations involving technology[2]. "Exposure to technological concepts and hands-on, design-related activities in the elementary and secondary grades are the most likely ways to help children acquire the kinds of knowledge, ways of thinking and acting, and capabilities consistent with being technologically literate[3]." Often, technological knowledge and concepts, especially in the elementary grades, are paired with fundamental design-based content and basic engineering associated processes. Although K-12 classrooms that incorporate engineering design content and

processes are emergent occurrences, they posses potentially successful qualities for not only engineering, but also for science, technology, and mathematics[4]. Katehi, Pearson and Feder further propose that engineering-based approaches in K-12 environments may expand student learning, therefore increasing achievement, in science and mathematics[4]. Additionally, employing engineering design content and processes may possibly increase awareness of engineering, engineering tasks, and engineering professions.

Current K-12 engineering infusion initiatives and efforts present themselves in various forms, ranging from single units of learning to full engineering academies. Although methods of implementation and models for integration vary for K-12 engineering, typically the curricula development and materials themselves are the focal point of investigation and study. In this project, prevalent materials (Engineering is Elementary) were selected to serve as the curricular basis for the structuring a data-informed elementary engineering model for grades 3-5.

Project Overview

The two-year National Institutes of Health funded project, Engineering Design Models in Elementary Schools, uses engineering design as an integral part of the full educational day. This fully integrated approach merges technological knowledge and concepts, fundamental design-based content, and basic engineering associated processes with the comprehensive study of mathematics, science, language arts, and social studies in an elementary school environment. This approach is unique, even among elementary engineering academies, magnet schools, and other specialty schools. More commonplace elementary engineering structures largely consist of specifically designated engineering courses, electives during the school day, or afterschool activities, rather than an integrated pedagogical approach. Utilizing a fully integrated approach does necessitate supplemental implementation features. The key integration features of the project include: extensive teacher professional development, cross-curricular grade level teacher planning, a student afterschool program, and ongoing programmatic alignment with the North Carolina Standard Course of Study. To inform the elementary engineering design model, academic effectiveness, progressions of student learning, progressions of student attitudes, and implementation fidelity were gauged. The research plan called for specific investigatation of student learning in design, engineering, and science; student attitudes toward STEM content; and teacher implementation and effectiveness.

Research Questions

As eluded to in the outline of the project framework, the overarching research question proposed and researched through this pilot study was: Does an integrated pedagogical approach that includes extensive teacher professional development, cross-curricular grade level teacher planning, a student afterschool program, and ongoing programmatic alignment promote student learning, student attitudes, and teacher effectiveness? Investigational hypotheses were derived, where appropriate, to provide specific evaluation of the project research question: a) There is no difference in student learning in engineering and design content knowledge before the onset of instruction and after participating in the integrated pedagogical approach; b) there is no difference in student learning in science content knowledge before the onset of instruction and after participating in the integrated pedagogical approach; c) there is no difference in student

attitudes toward STEM content before the onset of instruction and after participating in the integrated pedagogical approach. The teacher implementation and teacher effectiveness research aspects of the pilot test were gauged through a descriptive statistical display and an instuctional planning/process correlation matrix, respectively.

Methodology

This project model consists of four distinct phases: 1) Teacher professional development, 2) cross-curricular grade level teacher planning, 3) ongoing programmatic alignment, and 4) a student afterschool program. The teacher professional development phase of the project was led by a long-standing K-12 engineering outreach professional. The professional development project staff member who provided faculty development and implementation strategy for the pilot school is a certified trainer for the Museum of Science, Boston Engineering is Elementary curriculum. Elements of the staff development program included ensuring that all teachers possess a strong foundational understanding of Engineering, Science and Technology, use engineering as a core subject integration tool, use engineering/STEM notebooks as both a recording and assessment tool, implement project based learning approaches to instruction, understand connections between the North Carolina Standard Course of Study Science and Mathematics objectives and engineering curriculum, and effectively use the Engineering is Elementary curriculum in their grade level.

The STEM coordinator at the project pilot school administered cross-curricular grade level teacher planning. This process consisted of common joint planning for third, fourth, and fifth grade teachers. Each Thursday, third, fourth, and fifth grade teachers met with the STEM coordinator to identify course content to be delivered, lesson pacing and sequencing, materials needed, outcome documentation, and content integration strategies. The common joint planning concluded each week with addressing teacher concerns and suggestions for improvement concerning the previous week's content, process, and documentation. Each concern or suggestion was discussed and noted by the STEM coordinator for the next implementation phase. Additionally, the STEM coordinator ensured programmatic alignment through discussing core sequencing with whole-class elective subjects (physical education, music, chorus, art, and technology) and arranging thematic support content and activities.

Project staff administered the student afterschool program for pilot school students. Students selected for the afterschool program met at-risk criteria. Elementary students must typically meet one or more of the following categorical identifiers to be determined at-risk: Students identified with disabilities, students from economically disadvantaged families, or students with limited English proficiency[5]. Students with disabilities classification are previously determined by local education agency referral, evaluation, and determination of categorical disability. Hatch further identifies that economically disadvantaged classification is based on government aid to families, food vouchers, free or reduced-price school lunch, identified as a low-income family based on the Department of Health and Human Services Poverty Guidelines, or is a foster child based on abuse, poverty, or neglect[4]. Students with limited proficiency in reading, writing, and/or speaking the English language are included in at-risk determination[5]. The afterschool program consisted of project-developed engineering and mathematics learning activities incorporated on a weekly basis throughout the semester in the pilot school afterschool by project

staff.

The entire third, fourth, and fifth grades enrolled at the pilot school participated in the engineering-focused curricula. There were approximately 400 students enrolled at the school for the 2009-2010 academic year. The students were fairly evenly distributed over the three grades for the initial project academic year with approximately 80 third graders, approximately 70 fourth graders, and approximately 80 fifth graders. However, only the afterschool program students were administered project assessments and survey instrumentation.

The initial pilot test semester at a North Carolina public elementary school was conducted in the spring academic semester of 2010. The single pilot school was the only school considered in the initial year of National Institutes of Health funding. The project investigation used the pilot school afterschool program students to assess science understanding, engineering and design understanding, identify STEM attitudes, engineering self-efficacy, and student assessment of teacher effectiveness. This was accomplished through an online survey format. The STEM coordinator was sent a survey link for the students, the STEM coordinator prepared each computer in the school laboratory (accessed the link on each computer), students completed the assessments and surveys, the students clicked "submit" and the results were made accessible to the researchers in coded format. The pre-assessment of the Understanding Engineering Design instrument was administered January 20, 2010, and the post-assessment was administered April 14, 2010. The pre-assessment of the Understanding of Science instrument was administered January 27, 2010, and the post-assessment was administered April 15, 2010. The pre-survey of the Student Attitudes Toward STEM instrument was administered January 27, 2010, and the post-survey was administered May 5, 2010. The pre-survey of the Student Engineering Self Efficacy/Attitudes instrument was administered February 4, 2010, and the post-survey was administered May 6, 2010. The post-only Student Assessment of Teacher Effectiveness instrument was administered March 23, 2010.

Similarly, the teacher assessment of teacher effectiveness instrument links were sent to the STEM coordinator and distributed to the teachers via email. Project researchers conducted the student notebook review and the classroom observations on-site visits. The classroom observations and the Engineering Design Process STEM notebook evaluations were conducted on April 14, 2010.

Student attitudes and self-efficacy were gauged pertaining to STEM content and engineering capabilities. Additionally, information on student assessment of teacher effectiveness and classroom observation information was gathered. Student STEM notebooks were also evaluated to identify Engineering Design Model considerations and artifacts. The Understanding Engineering and Design Instrument, the Understanding Science Instrument, the Student Attitudes Toward STEM Instrument, and the Student Engineering Self-Efficacy Instrument were all implemented in pretest/posttest format. Hypothesis tests, descriptive statistical displays, and component variable breakdowns were tabulated and conducted.

Instrumentation

There is a range of instrumentation employed in this pilot study that corresponds to targeted investigational measures. Student participants and teacher participants take surveys and assessments in pre/post sequence as well as single measure format. The instruments have been developed/adapted and tested by numerous organizations, institutions, and researchers and were selected based on specific relevance for inclusion in the pilot study.

The Understanding of Engineering and Design assessment instrument is composed of 13 questions (eight multiple-choice and five select all that apply) that pertain to engineering and design concepts and considerations related to water purification, environmental considerations, agriculture considerations, materials concepts, and the engineering design process. Similarly, the Understanding of Science assessment instrument utilizes multiple-choice, select all that apply, and true or false questions associated with pollutants, the water states, pollination, and insecticides. The Students' Attitudes Toward STEM is a 19-item multiple-choice survey pertaining to STEM awareness, value, ability, and commitment. The Teacher Self-Efficacy in STEM Teaching survey is a 13-item Likert scale rating instrument ranging from 4 = very good to 1= poor. The content of the instrument includes abilities to promote and implement the use of problem solving, experimental design, observed and recorded data, and abstract concepts associated with science, technology, engineering, and mathematics.

The Student Assessment of Teacher Effectiveness Instrument (SATEI) and the Teacher Assessment of Teacher Effectiveness Instrument (TATEI) were developed to test the ability of teachers to implement inquiry-based learning, experimental design procedures, and teaching aids to facilitate student understanding of abstract concepts. The SATEI is based on a student perspective of teacher effectiveness of curricular implementation while the TATEI is a self-assessment. Both the SATEI and the TATEI are composed of 13 items and use a Likert scale ranging from 4 = very good to 1 = poor. The STEM notebook evaluation instrument is based on five criteria identified by the EiE Elementary Engineering Design Process. The four point scale used in the STEM notebook evaluation categorizes process components as 4 - Very Apparent: component is repeatedly addressed, 3 - Apparent: component is specifically and consistently addressed, 2 - Somewhat Apparent: component is implied but not directly mentioned, or 1 - Not Apparent: there is no evidence that the component is included. The classroom observation instrument is divided into three categories: 1) Lesson Design/Implementation, 2) Content, and 3) Classroom Culture. The lesson design/Implementation category has five specific observational measures and the content and classroom culture categories have 10 specific observational measures each. Each of the 25 observational measures is assigned a value based on the instrument scale criteria. Exemplary (5) is described as the "teacher demonstrates this competency consistently with a high degree of expertise and confidence relative to other teachers", above average (4) is described as the "teacher demonstrates this competency appropriately and frequently relative to other teachers", acceptable (3) is described as the "teacher demonstrates this competency appropriately but intermittently relative to other teachers, needs improvement (2) is described as the "teacher is developing skills in the competency but only occasionally demonstrates an appropriate level of proficiency relative to other teachers, and not acceptable (1) is described as the "teacher is lacking skills in the competency and rarely demonstrates attention and effort toward developing those skills.

Table 1 identifies the instruments used in the pilot investigation as well as the measurement structure and/or intent. Additionally, each instrument is specifically designated and noted for participant categorization as well as the originator or source of the instrument.

Table 1. Pilot instrumentation

Instrument	Measurement	Participant	Instrument Source
Understanding of engineering and design	Pre assessment and post assessment	Elementary students	Museum of Science, Boston
Understanding of science	Pre assessment and post assessment	Elementary students	Museum of Science, Boston
Student attitudes toward STEM	Pre survey and post survey	Elementary students	M.P. Mahoney, The Ohio State University[6]
Teacher self-efficacy in STEM teaching	Pre survey and post survey	Teachers	G.S. Schmitz & R. Schwarzer, Freie University, Berlin[7]
Student Assessment of Teacher Effectiveness Instrument (SATEI)	Single measure student perspective of teacher effectiveness of curricular implementation	Elementary students	E.O. Imhanlahimi & L.I. Aguele, Ambrose Alli University[8]
Teacher Assessment of Teacher Effectiveness Instrument (TATEI)	Single measure of self-assessment of teaching effectiveness	Teachers	E.O. Imhanlahimi & L.I. Aguele, Ambrose Alli University[9]
STEM notebooks	Overall STEM concept learning; engineering design learning; writing	Elementary students	National Institutes of Health Project Research Team
Classroom observations	Depth of engineering pedagogy; effect of using this implementation on their teaching	Teachers	American Association of Colleges of Teacher Education

Results and Findings

Student participant pre score and post score information associated with understandings of engineering and design, science, and attitudes toward STEM were entered and analyzed. The sets of data were analyzed through parametric methods, as they rely on the estimation of limits describing the distribution of the variable being investigated within the population.   Therefore, the methods require observations drawn from a normally distributed population while still allowing valid inferences about the samples. The single sample t-test is employed in this case, as

the researchers cannot conclusively pre-determine the population standard deviation and are left to estimate it by computing the sample standard deviation[10]. The pilot test results and findings are only attributed to third, fourth, and fifth grade student participants in a single school who were enrolled in a project afterschool program.

The first project hypothesis tested was: There is no difference in student learning in engineering and design content knowledge before the onset of instruction and after participating in the integrated pedagogical approach. This hypothesis was evaluated in Table 2 using the parametric single sample t test. The test statistic for single sample t test was compared to the designated critical value table based on the degrees of freedom for the sampling distribution. The critical alpha value was set at 0.05 for this investigation. The p-value for the test (0.0193) was determined to be smaller than 0.05; therefore, the null hypothesis is rejected. The analysis of data suggests that there was a statistically significant difference between students' engineering and design scores and design scores before and after the onset of the integrated pedagogical approach.

Table 2. Understanding of engineering and design

Difference	Sample Diff.	Std. Err.	DF	T-Stat	P-value
Pre Score - Post Score	0.871	0.352	30	2.472	0.0193

The second project hypothesis tested was: There is no difference in student learning in science content knowledge before the onset of instruction and after participating in the integrated pedagogical approach. This hypothesis was evaluated in Table 3, also using the parametric single sample t test. The p-value for the test (0.4038) was determined to exceed the predetermined 0.05; therefore, the null hypothesis failed to be rejected. The analysis of data suggests that there is no identifiable statistically significant difference between students' understanding of science scores before and after the onset of the integrated pedagogical approach.

Table 3. Student understanding of science

Difference	Sample Diff.	Std. Err.	DF	T-Stat	P-value
Pre Score - Post Score	0.367	0.433	29	0.847	0.4038

The third project hypothesis tested was: There is no difference in student attitudes toward STEM content before the onset of instruction and after participating in the integrated pedagogical approach. This hypothesis was evaluated in Table 4, also using the parametric single sample t test. The p-value for the test (0.5353) was determined to exceed the predetermined 0.05; therefore, the null hypothesis failed to be rejected. The analysis of data suggests that there is no identifiable statistically significant difference between student attitudes toward STEM before and after the onset of the integrated pedagogical approach.

Table 4. Student STEM attitudes

Difference	Sample Diff.	Std. Err.	DF	T-Stat	P-value
Pre Score - Post Score	1	1.591	26	0.628	0.5353

The Student Assessment of Teacher Effectiveness Instrument (SATEI) and the Teacher Assessment of Teacher Effectiveness Instrument (TATEI) were administered in a post-only format. The observation and evaluative information was tabulated to present in descriptive statistical displays (see Table 5). Mean, variance, standard deviation, standard error, and median were calculated for the SATEI and TATEI. The average SATEI rating for students was (43.517 of a possible 52). The variance (23.83) and standard deviation (4.882) of the SATEI are approximately the same when compared to the variance (23.583) and standard deviation (4.856) of the TATEI ratings. This indicates a similar spread of the project student participant ratings on the SATEI and the teacher participant ratings on the TATEI. The standard error (0.906) of the SATEI ratings for the student participant group is considerably smaller than the standard error (2.428) of the TATEI ratings for the teacher participants. This uncovered that student participants have less fluctuation in ratings from participant to participant on the assessment of effectiveness instruments. The medians of the student participants and the teacher participants exhibit minimal deviance from their groups' cumulative rating means, suggesting a somewhat symmetrical participant score distribution for both the student participants and teacher participants (refer to Table 5).

Table 5. Summary statistics for SATEI and TATEI

Instrument	n	Mean	Variance	Std. Dev.	Std. Err.	Median
SATEI	29	43.517	23.83	4.882	0.906	45
TATEI	4	86.25	23.583	4.856	2.428	87

Classroom observations were also conducted through a single instrument/observation. Similar to the SATEI and the TATEI the observation and evaluative information was tabulated to present in a descriptive statistical display (see Table 6). The classroom observation ratings for teachers were categorized into three major areas: 1) Lesson Design/Implementation, 2) Content, and 3) Classroom Culture. Mean, variance, standard deviation, standard error, and median were calculated for the classroom observations. The variances and standard deviations of the categorical observations are approximately the same indicating a similar spread of the project observable teacher categories. The standard error (0.26) of the Lesson Design/Implementation category is closely assigned in comparison to the standard error (0.186) of the Content category and the standard error (0.17) of the Classroom Culture category. This uncovered that teacher participants have little fluctuation in observation ratings from participant to participant on the three categories. The medians of the student participants and the teacher participants exhibit

minimal deviance from the cumulative observation means, suggesting a somewhat symmetrical distribution for all three observation categories (refer to Table 6).

Table 6. Summary statistics for classroom observations

Category	n	Mean	Variance	Std. Dev.	Std. Err.	Median
Lesson Design/ Implementation	10	4.3	0.678	0.823	0.26	4.5
Content	10	4.2	0.695	0.834	0.186	4
Classroom Culture	10	3.95	0.576	0.76	0.17	4

Student STEM notebooks were kept by students throughout the school day. A key component of the project pedagogical model was the elementary engineering design process developed by Engineering is Elementary. The process stages of the engineering design process include an imagine, a plan, a create, an improve, and an ask stage. Student notebooks were selected at random and evaluated using a four-point evaluation scale by a National Institutes of Health project researcher. Sketches, diagrams, charts, notes, and bulleted points in each notebook were categorized into process stages and noted for evaluation specifically concerning degree and depth of consideration/implementation of the elementary design process. The overall means, variances, standard deviations, standard errors, medians, and ranges are documented for each process stage (see Table 7). The "create" mean (3.3 of a possible 4) was the highest and the "ask" mean was the lowest. This indicates that the sample of student notebooks evaluated, as a whole, had a lesser degree of consideration for the process stage "ask" than the other process stages while having a more apparent consideration for the process stage "create". The higher variances and standard deviations for process stages "plan" and "create" indicate larger analysis spreads that the smaller variances and standard deviations for process stages "improve" and "ask". Although relatively low, the standard error was slightly larger for process stages "plan", "create" and "imagine" and lower for process stages "improve" and "ask". This identified that overall student notebook evaluations have minimal fluctuation from participant to participant on the five process stages.

Table 7. Summary statistics for student STEM notebooks

Stage	n	Mean	Variance	Std. Dev.	Std. Err.	Median
Imagine	10	2.5	0.278	0.527	0.167	2.5
Plan	10	2.5	0.5	0.707	0.224	2
Create	10	3.3	0.458	0.675	0.213	3
Improve	10	2.9	0.1	0.3168	0.1	3
Ask	10	2	0	0	0	2

Conclusions

Many issues face the United States today that have political and economic ramifications and also require an understanding of science and technology. The general public is called upon to make political and practical decisions on these issues. The paradigm for understanding and appreciating the designed world is changing. In many ways the lifestyle we enjoy today depends on engineering and engineers. Engineering education is not only practical but vital for all children. Continued research on how to best approach engineering and technology education is of utmost importance to contribute to a knowledgebase that enhances understandings of how to best approach, introduce, and infuse engineering and design into school curricula.

These research results provide insight, assisting project efforts to structure a data-informed elementary engineering model for grades 3-5. As evidenced by pilot results associated with content/process gains in engineering and design, an integrated pedagogical approach can lead to integrated competency building. Engineering is a tool for integrating the other STEM disciplines, as well as language arts, social studies and the arts. It provides for a deeper awareness and practical knowledge of how the subjects are connected and applied to daily life.

In this study, summary statistics of classroom observations identify observer agreement in pilot teachers attaining benchmarks associated with lesson design/implementation, content, and classroom culture. However, without the establishment and implementation of a model many teachers are unprepared to use updated teaching techniques, such as guided inquiry, in the classroom. This leaves relevance and application virtually unachievable in the K-12 classroom in many instances. Engineering naturally integrates various core disciplines. It is a vehicle to bring rigor, relevance and context to the teaching of the other three subjects in an integrated manner.

One of the hurdles to excellent teaching and learning in science in particular is the perception by students that the concepts lack relevance in daily life. This perception is historical and pervasive. In conclusions of a Delphi study conducted by Harris and Rogers, the affective domain and personal attributes of students should serve as central considerations in any K-12 technology and/or engineering education course or sequence[11]. This study gauged the affective domain and identified positive progressions in student attitudes toward STEM content and disciplines and the student engineering self-efficacy when participating in the integrated pedagogical approach. Teaching in K-12 through engineering can be a stealth approach to reaching children that have not and are not being reached in the teaching of isolated subjects. At the elementary level, where teacher preparation is of a general nature with regards to core subjects, engineering can not only provide teachers with a path to relevance but also result in their own content knowledge comfort level increasing through the application of the theory.

The field test of the integrated pedagogical approach is currently being conducted. Data are being gathered to determine if an expanded duration of exposure enhances student competency associated with engineering, design, and science. Supplemental to competency, it is being investigated if expanded exposure to the professional development sequence enhances curricular implementation and the infusion of effective instructional elements in the grades 3-5 classroom. Also, all pilot measures are being conducted in two new project schools to identify any initial

progressions. Pairing this pilot study with current field-test measures will provide the means to structure data-informed educational process, enhanced classroom application, as well as a research-based integrated pedagogical approach for elementary schools.

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