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Board 186: Work in- Progress: Scaling STEM-ID—Research Strategies to Inform Initial Scaling of Middle School Engineering Curricula

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Abstract

This work-in-progress paper discusses STEM-ID (STEM-Innovation and Design), a three-year middle school Engineering and Technology course sequence. STEM-ID courses integrate foundational mathematics and science in an engineering context through challenges that introduce students to advanced manufacturing tools such as computer aided design (CAD) and 3D printing and incorporate engineering concepts such as pneumatics, aeronautics, and robotics. This paper will describe research strategies informing the initial scaling of the STEM-ID curricula following its iterative development over several years during a previous grant. Specifically, we will describe the data sources being utilized to inform refinement of curriculum materials and the project's professional development (PD) model. Funded by a National Science Foundation (NSF) Discovery Research K-12 (DRK-12) grant, the project seeks to scale the STEM-ID curricula in a large urban school district. Utilizing Design-Based Implementation Research (DBIR) as a guiding framework, the project strives for an iterative, collaborative design process that prioritizes practitioner involvement and the consideration of multiple stakeholders' perspectives. In the first year of the project, data collected from six teachers at five schools include surveys, observations, interviews, and focus groups. Drawing on this data, we will present illustrative examples and strategies the project has developed for collecting and synthesizing implementation data and teacher feedback to inform scaling efforts. The findings have practical implications that will help teachers and researchers in the engineering education community scale engineering curricula and teacher professional development models.

Introduction

With an increased focus on engineering in K-12 education, there is a pressing need for understanding conditions necessary for successfully implementing and sustaining authentic engineering curricula [1], [2]. A review committee commissioned by the National Academy of Engineering (NAE) in collaboration with the Board on Science Education at the National Academies of Sciences, Engineering, and Medicine, describe how "high-quality content knowledge varies across grade levels…" and "…specific instructional practices that support students' integration of engineering with concepts and practices from other STEM subjects," as pressing issues driving professional development [1]. However, since curriculum innovations that work in some educational settings may not work in others [3], educators need guidance on how to balance innovation and implementation that can be sustained and maintained through teacher-informed classroom practices, especially when meeting the needs of diverse learners. Understanding how and why innovations in engineering education work is necessary for replicating success across classrooms and school districts.

Middle school engineering continues to be an important area of research. With growing evidence of positive identity development in middle school students experiencing engineering curricula [4], scaffolding knowledge at this level is an important aspect of continuing to build students' interest in studying engineering [5]. Such experiences help to improve student self-efficacy and attitudes toward STEM and facilitate students' understanding of engineering during a crucial period of integrated scientific inquiry and engagement. The Science, Technology, Engineering, and Mathematics Innovation and Design (STEM-ID) Curricula developed at the Georgia Tech

Center for Education Integrating Science, Mathematics and Computing (CEISMC) integrate foundational mathematics and science in an engineering context through challenges that introduce students to advanced manufacturing tools and incorporate engineering concepts, thus engaging students in an authentic engineering learning experience. While prior studies documented the success of this curriculum in improving students' attitude towards learning science and mathematics and an overall positive experience in engineering design activities [4], researchers now seek to develop new understandings about STEM-ID implementation and outcomes to inform future implementation in increasingly diverse school contexts.

As the demand increases for high-quality, research-based engineering resources, researchers and teachers need to understand the factors that influence the scaling of innovations. Teachers and other stakeholders want innovations that are adaptable over various contexts and strategies to sustain them [3]. Studies rooted in collaboration, inquiry, and multiple perspectives on pedagogy can illuminate such research efforts and inform the sustainability of curricular innovations. The purpose of this study is to describe research strategies that have informed curriculum refinement and professional development during the initial scaling of the STEM-ID curricula.

Frameworks

Informed by a tradition of "practice-embedded research" [6], our research on the STEM-ID curriculum occurs at the intersection of research and practice. Snow describes the value of practice-inspired educational research, stating:

> Knowing what aspects of a new program or practice are easy or hard to implement, which ones are adopted after minimal versus only after intensive professional development, which are embraced by teachers, and which rejected is crucial to designing new innovations that are likely to take [6, p. 461].

To this end, the study is informed by two conceptual frameworks: Design Based Implementation Research (DBIR) [7] and the Innovation Implementation Framework [8].

Design Based Implementation Research

Fishman et al. [7] identify four principles of DBIR that guide the current study. The first is a focus on "problems of practice" and the consideration of such problems from multiple perspectives. This principle informs the study's intentionality around recruiting engineering teachers to implement STEM-ID in diverse classroom settings and developing research strategies to identify and address problems of practice in middle school engineering classrooms. The second DBIR principle is the commitment to a collaborative design process. The project proactively elicits feedback and encourages involvement of participating teachers in the refinement of the curriculum and development of new resources. The third principle, the use of systematic inquiry to develop theory and knowledge related to learning and implementation, is evident in the study's triangulation of data sources to develop new understandings about teaching and learning in middle school engineering classrooms. The fourth principle emphasizes concern for building capacity for sustaining change at the system level. In addition to understanding current implementations of STEM-ID, our research is conducted with an eye toward necessary conditions and potential challenges of scaling STEM-ID.

Innovation Implementation Framework
While the tenets of DBIR guide the project's overall research agenda, the Innovation Implementation Framework [8], [9] guides our research on curriculum implementation. As detailed in a previous publication [10], the Innovation Implementation Framework provides a useful conceptual framework for identifying and describing the implementation of critical components of the STEM-ID curriculum. Century and Cassata [9] define innovation implementation as "the extent to which innovation components are in use at a particular moment in time" (p.87). Thus, innovations are conceptualized as being complex, time-bound, and constituted by essential parts or components. Definitions of the types of components within the framework and the specific critical components of the STEM-ID curriculum are presented in Table 1. Century and Cassata [9] distinguish between research examining *implementation fidelity*, in which implementation data is compared to a theoretical ideal, and investigations focused on *innovation use*. Because innovations (including STEM-ID curricula) are rarely, if ever, implemented exactly as designed, we have found that measuring how the various components of an innovation are used is often more informative than focusing on overall measures of implementation fidelity. In addition to understanding how various components of STEM-ID were enacted in engineering classrooms, we draw on Century & Cassata's companion Factor Framework, to describe factors across various categories (e.g., characteristics of the innovation, users, organization) that may influence STEM-ID enactment.

Methods

Curriculum: The STEM-ID curricula is comprised of three, semester-long 6^{th}, 7^{th}, and 8^{th} grade engineering courses, each designed to develop specific, foundational STEM skills leading up to a final design challenge. Table 2 summarizes the major activities included in each grade-level course. Based on promising results following an approximately 4-year initial development and implementation period in one school district, our research team has launched a new NSF-funded project designed to scale STEM-ID to reach a broader population of engineering teachers and students. To this end, during the 2022-23 school year, STEM-ID is being implemented by a new cohort of six teachers in five schools within a much larger school district, with plans to add additional cohorts for the next three years.

Participants: Participants are six teachers from five middle schools in the second largest county of a metro city located in the southeastern part of the United States. The group includes two males and four females, with engineering teaching experience varying from zero to eight years, and two of the five teachers co-teaching at the same school. Teachers' backgrounds include mathematics, science, and computer science teaching, with three teachers having over 20 years of teaching experience, two teachers with 15 and 18 years each, and one teacher with five years. The five schools report between 60 and 95 percent minority enrollment and the county is considered to have one of the most diverse student populations within the state.

Data Sources

This study triangulated multiple data sources including professional development observations, teacher interviews, and enactment checklists to explore and understand teachers' curriculum implementation and the role of professional development (PD) in this process.

Observations: Observations of PD took place over the course of five days, with one researcher observing all five days and other researchers observing the same professional development sessions for one to two days. Classroom observations were also conducted in each teacher's classroom over a 2-week period at the end of the semester. Both PD and classroom observations used protocols adapted from the project's previous research that included space to record field notes pertaining to each critical component of the curriculum, teacher characteristics that may influence implementation (e.g., background, self-efficacy, understanding of the curriculum), as well as indications of any potential adaptations that teachers plan to make or challenges, they anticipate as they implement STEM-ID.

Teacher Interviews: Teacher interviews were conducted using both informal and formal approaches. Teachers attended monthly online check-in meetings lasting about 60 minutes where they were invited to share progress on implementation and ask questions of the project team and each other. The check-ins served to obtain implementation data and foster a learning community among teachers. These informal discussions were recorded and summarized within one week of each discussion in order to share teacher feedback related to critical components, adaptations, and challenges with the project team. At the end of the first semester of implementation, researchers conducted semi-structured, in-person interviews, lasting 45 - 60 minutes. These interviews were guided by a protocol including questions and follow-up prompts aligned to each critical component along with questions designed to elicit reflections on factors influencing implementation. These interviews were recorded and transcribed for analysis.

Enactment Checklists: Teachers completed enactment checklists in the form of online surveys completed at the end of each grade level challenge. These checklists asked teachers to report on whether they implemented key activities within each of the grade level challenges. The checklist surveys also invited teachers to share any adaptations they made, or challenges encountered as they implemented each challenge.

Results

Below, we present two illustrative examples to highlight how the project's approach to data collection and analysis informs decision-making around refinement and development of new resources to support scaling of the STEM-ID curriculum.

Example 1: *A Componential Approach to Studying Implementation*

As in our previous STEM-ID research [10], we found great utility in taking a componential approach to studying implementation of STEM-ID as it was implemented in five new schools. Rather than attempting to develop comprehensive accounts of implementation across STEM-ID challenges to arrive at an aggregate assessment by grade level or teacher, we found it far more fruitful to organize our data collection, analysis, and reporting around the critical components of STEM-ID. In particular, examining critical components has allowed us to identify specific implementation challenges and opportunities for curriculum refinement that would likely have been obscured if we had taken a more general approach. Table 3 presents an implementation matrix developed to illustrate implementation by critical component for each teacher based on preliminary data gathered during the first semester of implementation. These types of matrices provide useful high-level overviews of patterns of implementation across teachers and critical components. For example, in this matrix, we see evidence of potential issues related to the

Advanced Manufacturing and Technology component across teachers along with variations in implementation across teachers.

In addition to providing valuable insight into implementation patterns, analysis of various data sources by critical component enables targeted development of new resources to support current and future STEM-ID teachers. For example, analysis of PD observation data focused on facilitation of the engineering design process revealed potential challenges related to the assembly of the pneumatic catapult used in the 6th grade Systems Challenge. Specifically, teachers were concerned about the time required to assemble catapults and demonstrated that they weren't always adept at making necessary adjustments to the catapult settings. Because proper use of this equipment is critical for students' collection of data to inform their work in the design challenge, our summary report on PD observations included a recommendation that the project develop catapult assembly videos featuring tips and tricks for the assembly and use of the catapults. Our research team then developed "Tech Talks," short videos of no more than five minutes, that teachers could access when planning to implement the 6th grade data challenge.

Example 2: *Establishing Feedback Loops Between Research and Practice*
In the spirit of DBIR, we utilized information learned from teacher implementation experiences to inform innovations in curriculum materials. In one case, an issue of obsolescence surfaced with LEGO NXT and EV3 sensors. As teachers began implementing the 8th grade curriculum, we learned through check-in meetings and regular email correspondence that they were encountering an array of technical issues with certain versions of the LEGO software used in the challenge that were no longer being supported. Specifically, teachers found that their school system was no longer supporting updates to the EV3 software that students use to collect data during the 8th grade Systems and Investigation Challenge. This meant that teachers either skipped important data logging activities or developed workarounds, such as presenting pre-collected data rather than having students collect data themselves. Both of these options compromise student learning related to math integration and the use of advanced manufacturing technology (robotics). Having anticipated the obsolescence of the LEGO NXT and EV3 kits, members of our team had begun to conceptualize an alternative. Learning about the frustrations our current teachers were encountering confirmed the need to fast-track the development of a 3D-printed chassis to replace the existing LEGO platform. This version will use MicroBit and therefore be agnostic to the particular version of LEGO robotics a teacher has available to them in their classroom. The current prototype of this 3-D printed version (Figure 1) is being tested for potential use in classrooms next school year. Thus, in addition to addressing a problem of practice reported by our current STEM-ID teachers, this new resource will potentially facilitate scaling as STEM-ID is implemented more broadly in setting with varying access to LEGO robotics materials.

Example 3: *Leveraging Teacher Experiences in Establishing Teaching Strategies*
The third example expounds further on DBIR's principle of identifying and addressing "problems of practice." In regular check-in meetings, teachers share pedagogical insight on their implementation experiences. In one check-in, a teacher with substantial science teaching background shared how he used the scientific method to introduce the engineering design process, and that his special education students responded well to the scaffolding used to teach the EDP to meet their learning needs. The need to support development of another foundational

skill, measurement, surfaced consistently during conversations. Teachers described that some students “struggle with measurement and connecting the sketches to the CAD drawing and to the prototype,” and “translating it from physical measurements into TinkerCAD.” Two teachers offered advice on teaching measurements in another check-in. They explained: “We use a chart of all the plane parts for students to use during wing piece construction and have them fill in the measurements.” Furthermore, they remarked how this approach was good for students when designing their own wings, thus giving “them a clue as to what measurements to start with.” They also affirmed teachers’ observations of the lack of some prerequisite skills saying, “it’s amazing how little math[emetics] carry over…especially in 6th grade, it’s like they forget all their math training when they walk out the door.” Teachers seemed to respond well to this advice and its pertinence to their implementation goals and pedagogical needs.

Conclusion

Through this study, we observed teachers utilizing various resources, both formal and informal, to enhance their STEM-ID implementation experiences in their middle school engineering classrooms. The componential approach identified implementation issues across grade levels and between schools, which provide valuable insight towards scaling efforts and professional learning. Furthermore, teacher-researcher feedback loops offered targeted feedback relevant to teachers’ real time lesson planning and implementation. These preliminary results, along with complete analysis of teachers interviews and informal check-ins may reveal even more practices and strategies critical to understanding effective K-12 engineering pedagogy. Additionally, our findings and the corresponding professional development models produced may also help to support continued efforts toward sustainable curriculum expansion.

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Table 1
STEM-ID *Critical Components*

<table>
<tr><th colspan="2">Structural – Procedural Component</th><th>Structural – Educative Component</th></tr>
<tr><td colspan="2">1. Course organized according to contextualized problem-based challenges.</td><td>2. Utilization of Curriculum Materials including: Teachers' Edition, materials and supplies related to design challenges, challenge overviews, information on related Math and Science standards, instructions for preparing and utilizing technology (3-D printers, LEGO Robotics, CAD software), digital Engineering Design Logs</td></tr>
<tr><th colspan="3">Interactional Components</th></tr>
<tr><td>Component Area</td><td>Teachers</td><td>Students</td></tr>
<tr><td>Engineering Design Process</td><td>3. Teacher Facilitates Student Engagement in the Engineering Design Process</td><td>4. Students Engage in the Engineering Design Process</td></tr>
<tr><td>Math/Science Integration</td><td>5. Teacher Facilitates Integration of Math/Science and Engineering</td><td>6. Students Apply Math/Science Content and Skills</td></tr>
<tr><td>Advanced Manufacturing Technology</td><td>7. Teacher Facilitates Utilization of Advanced Manufacturing Technology</td><td>8. Students Use Advanced Manufacturing Technology</td></tr>
<tr><td>Collaborative Group Work</td><td>9. Teacher Facilitates Collaborative Group Work</td><td>10. Students Engage in Collaborative Group Work</td></tr>
</table>

Table 2

STEM-ID Curriculum Overview

Course	Description
6^{th} Grade "Carnival Tycoon"	Students explore the engineering design process and entrepreneurial thinking in the context of a carnival. The course begins with students making a sales pitch for a new carnival food stand based on market research. Students then run experiments using a pneumatic catapult, and they must design a new carnival game board with appropriate odds of winning. Then, after skill development in engineering drawing, they re-design the catapult cradle to change the performance characteristics of their carnival game. Students incorporate math and science content, including data representation, probability, experimental procedures, profit calculations, drawing, and measurement.
7^{th} Grade "Flight of Fancy"	Students pose as new airline companies and redesign airplanes to be more comfortable, profitable, and environmentally friendly. This is accomplished through a series of challenges, starting with a test flight of different Styrofoam gliders. Students examine interior layouts, learn 3D modeling in Iron CAD, and finally, re-design a plane using a balsa glider as a model. Students incorporate math and science content, including measurement, proper experimental procedure, data analysis, and profit calculations.
8^{th} Grade "Robot Rescue"	The course is intended to further build student understanding of the engineering design process and entrepreneurship. The course begins with a short design challenge, requiring the students to design and 3D print a cell-phone holder. Students then conduct experiments using a bio-inspired walking robot. The course ends with an open-ended challenge to design a rescue robot capable of navigating variable terrain. During these challenges, students use LEGO® Robotics, 3D CAD modeling software, and 3D printing technologies. In addition, students incorporate math and science content, including modeling, data analysis, scientific procedure, force and motion concepts (e.g. velocity, speed, friction), and systems thinking.

Table 3

Preliminary Implementation Data of STEM-ID Critical Components by Teacher

Critical Component	T1	T2	T3	T4	T5	T6
1. Course organized according to contextualized problem-based challenges.						
2. Utilization of Curriculum Materials						
3. Teacher Facilitates Student Engagement in the Engineering Design Process						
4. Students Engage in the Engineering Design Process						
5. Teacher Facilitates Integration of Math/Science and Engineering						
6. Students Apply Math/Science Content and Skills						
7. Teacher Facilitates Utilization of Advanced Manufacturing Technology						
8. Students Use Advanced Manufacturing Technology						
9. Teacher Facilitates Collaborative Group Work						
10. Students Engage in Collaborative Group Work						

Implementation Categories	None	Component not implemented.
	Partial	Component partially implemented: aspects of component implemented according to curriculum. Some adaptations, omissions, and/or additions misaligned with curriculum and its goals.
	Full	Component fully implemented. Any adaptations, omissions, or additions align with the curriculum and its goals.