Integrated STEM Models of Implementation

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Abstract

Within this decade, programs to improve STEM education are too numerous to count with efforts at the federal, state, and local levels. From targeted teacher professional development to totally reinventing teacher preparation programs, these efforts have helped to identify, develop, and deliver integrated STEM education programs; however, the question of how integrated STEM programs are best implemented in K-12 classrooms remains ill-defined. This mixed methods study seeks to understand how integrated STEM programs are implemented in K-12 schools. The findings describe four schools' approaches to implementing an integrated STEM program. With the collaborations of teacher pairs, each consisting of an engineering technology education (ETE) and a life sciences teacher, they worked to implement integrated STEM lessons using engineering design and science inquiry practices, biomimicry, and 3D printing to enhance learning STEM content. Three distinct models of integrated STEM implementation emerged from the case study findings and additional quantitative methods assess which model most effectively taught STEM content knowledge to secondary students. An ANOVA test result shows that there was a significant difference between groups in student STEM knowledge test scores. The mean score increases for students within the collaborative teacher models were significantly higher than the student scores within the single teacher inclusion model.

Introduction

There is great concern on a global scale to improve STEM education as the demand for STEM-skilled workers is necessary to overcome economic challenges of the 21st Century (Partnership for 21st Century Skills, n.d.; Rockland, Bloom, Carpinelli, Burr-Alexander, Hirsch, & Kimmel, 2010). Furthermore, even though there is demand for STEM expertise, enthusiasm toward STEM learning has been on a decline among students across the globe (Thomas & Watters, 2015). United States government agencies as well as secondary to higher education are promoting the development of integrated STEM curricula that can impact and engage all students. These actions have also created an urgency for more research investigating integrated STEM models that impact student learning and generate interest in STEM careers.

From 2010 until now, there has been a great effort in STEM education reform in the United States. These efforts are evident in many standards, policies, and national research studies on the topic of STEM education (Honey, Pearson, & Schweingruber, 2014). However, there are many constraints limiting the success of integrated STEM efforts, including but not limited to:

a) lack of time needed to fully implement STEM lessons;
b) cost of projects, materials, and special tools;
c) lack of quality integrated STEM curriculum;
d) pressures from end of course assessments (Dare, Ellis, & Roehrig, 2018; Dugger, 2010; Ejiwale, 2013; Ntemngwa & Oliver, 2018; Sanders, 2009).

It is very possible the most challenging constraint impeding integrated STEM efforts is the existing school structures (Dugger, 2010). These school structures, both physical and organizational, were designed to teach science, mathematics, and technology in silos. Science teachers are prepared to teach science, math teacher prepared to teach mathematics, and engineering technology education teachers prepared to teach design, technology, and engineering concepts. Moreover, some schools do not offer any engineering technology education courses until grade six if at all. Teachers and school officials must locate ways to overcome these obstacles for integrated STEM learning to be realized. It is clear that schools and teachers lack models of implementing integrated STEM education that can help overcome these barriers while successfully integrating STEM content. For teachers and school administrators to embrace integrated STEM teaching and learning, they must be provided with practical implementation models of successful STEM integration. To create sustainable approaches to integrated STEM, these models of integration must be born out of existing school structures built around traditional classrooms, typical school schedules, common curricula, and national and state learning standards. Policy makers must listen to the voice of teachers in K-12 practice to understand the constraints and barriers that currently exist within school structures (Brand, 2020).

Science Education and Engineering Technology Education (ETE) Opportunities for Integration

There have been considerable efforts in science education reform to include engineering practices and engineering content within the science curriculum, including learning standards mapping engineering practices and content to science curriculum, updated science textbooks mapped to NGSS, and teacher professional development opportunities focused on integrating engineering design into science, (NGSS Lead States, 2013). Prior to this education reform, science education has a history of exploring design as a platform to engage students and promote science learning (Beneson, 2001; Crismond, 2001; Fortus, Dersgumer, Krajcik, Marx & Malok-Naaman, 2004; Kolodner, 1997; Wendell & Rogers, 2013). Similarly, there have been efforts in technology education to include engineering design as an approach to promote technological literacy (Dearing, & Daugherty, 2004; Hailey, Erickson, Becker, & Thomas, 2005; Hill, 2006; Lewis 2004; Sanders, 2009; Wicklein, 2006). While science education is new to teaching design, technology education has decades of history in design education in K-12. Additionally, technology educators have labs equipped with prototyping tools, including 3D printers, laser cutters, digital electronics, and advanced manufacturing tools that help promote teaching engineering design. However, although engineering technology teachers have expertise in prototype building and teaching design, they have limited experience using scientific inquiry to inform the design process (Lewis, 2006; Ntemngwa & Oliver, 2018). The common practices of engineers and scientists have many similarities, which are well documented in the *Frameworks for K-12 Science Education* (National Research Council [NRC], 2012). Technologist practices are also similar to science practices (Kolodner, 2002) and provide an opportunity for collaboration. Lewis (2006) specifically documented the parallels between design and science inquiry and challenged both science and technology education teachers to collaborate due to the natural similarities of these practices, thus, to provide cross-curricular synergies. In other words, there exists the opportunity for science and engineering technology education (ETE) teachers to partner up to improve integrated STEM teaching and learning while promoting science and engineering practices (NRC, 2012). An additional benefit for both students and teachers is to provide more opportunities to use advanced technologies to enhance STEM learning that can only be made possible from technology experts (technologists). However, even though there has been a growing interest for integrating science and engineering, empirical research on this teaching approach is limited. Furthermore, teachers and school administrators lack examples of how teachers from different domains can work together to truly integrate subjects when within their school schedules and class structures, and acrosslearning standards, and assessments. A lack of these examples suggests that it is easier to 'shut the door' and teach your own discipline. Thus, research on how teachers should develop approaches to integrated STEM and practical approaches to support students' STEM learning is necessary (Honey et al., 2014; Ntemengwa & Oliver, 2018). The National Science Foundation (NSF) through the Innovative Technology Experiences for Students and Teachers (I-TEST) project seeks to promote strategies for engaging students in technology-rich experiences that: 1) increase student's awareness in STEM occupations; 2) motivate students to pursue STEM careers; and 3) develop disciplinary-based knowledge and practices (National Science Foundation [NSF], n.d.). We believe that science and ETE teachers can achieve these outcomes, given the opportunity to collaborate and create integrated STEM learning experiences. In 2016, the National Science Foundation funded an I-TEST project called *Teachers and Researchers Advancing Integrated Lessons in STEM* (TRAILS) (NSF award #DRL-1513248) that was an effort to bring life science and engineering technology education teachers together to improve STEM learning for high school students. TRAILS aimed to engage high school science and ETE teachers in professional development to build STEM knowledge and practices to enhance integrated STEM instruction. Additionally, TRAILS established a community of STEM practice with teachers, industry partners, professors, and college students. TRAILS also engaged high school students in STEM learning through engineering design and 3D printing prototypes. The TRAILS teachers and students were recruited from rural school's settings to overcome barriers for these underserved populations (Biddle & Azano, 2016; Graham & Provost, 2012; NRC, 2014).

Challenges Associated with Integrated STEM Implementation

Several challenges have been identified by previous studies in implementing an integrated STEM education program. These challenges can be classified as pedagogical and technical, including both external and personal constraints (Dare et al., 2018; AUTHORS, 2016; Moore, Stohlmann, Wang, Tank, Glancy, & Roehrig, 2014; Nadelson, Seifert, Moll, & Coats, 2012). Teachers confront challenges incorporating several disciplines together while maintaining students' interests. Teachers also face challenges acquiring technical or scientific knowledge, which is necessary for integrating the contents appropriately. Especially for science teachers, technical support from technology teachers is critical. In addition, external or personal constraints such as planning time and overall instructional time were barriers. Teachers often do not have the right amount of time to implement an integrated STEM lesson or unit (Dare et al., 2018; Ntemengwa & Oliver, 2018). Other challenges, including the lack of integrated STEM professional development and integrated STEM lessons, were also identified by previous researchers (English, 2016; Roehrig, Wang, Moore, & Park, 2012). Regarding integrated STEM instruction, Dare and colleagues (2018) pointed out that the degree to which integrate STEM content was fully realized may depend on the teacher's ability to connect the disciplines explicitly (Dare et al., 2018).

Although integrated STEM initiatives have become popular recently and there is an increase in research on the positive impact of STEM education, these integrated approaches to teaching have not become a pedagogical norm in most secondary schools. Additionally, research on how teachers should develop an integrated STEM context is needed for practical strategies to support students' STEM education (Honey et al., 2014; Ntemengwa & Oliver, 2018). There is a high need for researchers to document in detail how teachers successfully implement STEM programs, as well as pedagogical approaches to STEM curriculum (Kelley & Knowles, 2016). Moreover, it is important to allow teachers to share their perspectives, experiences, and approaches to STEM education as a way to establish best practices in integrated STEM education. Research is necessary to capture teachers' voices sharing their experiences, perspectives, and teacher-developed approaches to integrated STEM.

Methods

Research Design

The researchers obtained human subjects approval from Purdue University Internal Review Board to conduct a research study with high school teachers and students participating in the TRAILS program. In this study, how science and engineering technology teachers implemented co-created integrated STEM lessons in their classrooms was explored. The researchers hypothesize that teachers can be positive agents of change and therefore we are studying how they choose to implement integrated STEM lessons and investigate the impact of their approach on students' learning STEM content. We hypothesize that these teachers will develop approaches that can become models of implementation to promote student learning while overcoming barriers to integrated STEM education all while maintaining key features of the TRAILS program.

Below is the overarching research question and sub questions that guided this mixed methods case study. What models of integrated STEM teaching emerge from the teacher pairs during implementation?

a. What were the features of the intervention (TRAILS program) that were implemented in the classroom?
b. What features of the intervention were emphasized?
c. What barriers did teachers encounter and how did they overcome them?

Which model or models of integrated STEM were the most effective approach to teaching STEM content?

a. How do the three models compare as measured by students' STEM knowledge test results?

This study will first use a case-based approach to research to identify teacher implementation models to answer question 1 and sub questions. Next, the researchers will use a pretest-posttest STEM knowledge assessment to answer research question 2.

As with all qualitative research, the researchers were interested in how meaning was constructed through three cases with the overall goal to discover and interpret these meanings (Daher, Carré, Jaramillo, Olivares, & Tomicic, 2017; Hunter, Lusardi, Zucker, Jacelon, & Chandler, 2002). This case study describes how integrated STEM education could be practiced in high school classrooms. In this study, qualitative data, which consists of teacher interviews, teacher focus groups, and other curriculum materials were collected by the researchers and analyzed following Merriam's (1998) cross-case analysis method. Due to the relatively new construct of teaching integrated STEM education, it was deemed appropriate to use this approach to cross-case study research. Merriam's approach can result in a unified description across multiple cases with the potential to create typologies, categories, or themes. Sometimes Merriam's methods can externalize the data from all the cases in order to form an essential theory, thus, create an integrated framework that covers multiple cases (Creswell, 2013).

Context of the Study

TRAILS was a three-year-long project funded by the National Science Foundation (NSF). Every year, high school science and engineering teachers participated in a summer professional development for two weeks. During the professional development and throughout the school year, researchers, educators, and industry partners collaborated to provide a variety of STEM learning opportunities for the teachers.

A total of 43 STEM teachers participated in the project, and 20 integrated STEM lessons (one exemplar lesson developed by the researchers and nineteen custom lessons developed by the researcher-teacher collaboration) were implemented in 47 STEM classrooms over three years (2016-2019 academic years).

Sample Selection

Purposeful sampling was employed for an in-depth understanding of the integrated STEM education models that can be applied to classrooms. "Purposeful sampling is based on the assumption that the investigator wants to discover, understand, and gain insight and therefore must select a sample from which the most can be learned" (Merriam & Tisdell, 2015, p. 96). The researchers established the criterion for sample selection for recruiting teachers to participate in this study as follows:

a) successful implementation of two TRAILS lessons, one exemplar and one teacher custom lesson
b) dedication to teaching using an integrated STEM approach;
c) strong collaboration with the teacher partner;
d) strong communication skills with TRAILS team; and
e) participation in TRAILS community of practice.

Criteria a and b were assessed by reviewing teachers' implementation plans showing necessary teaching time of the TRAILS units as well as successful completion of student and teacher surveys and STEM knowledge assessments. Criteria c and d was assessed as teachers reported out during follow-on sessions with the TRAILS leadership of their experiences in implementing lessons and partnering with their colleague. TRAILS leaders learned from these early conversations of strong teacher partnerships as well as teachers' willingness to respond to emails and focus group request. Criterion e, participation in the community of practice (CoP) was determined by the amount of time teachers dedicated to participating in follow-on sessions, seeking community experts in their school community to add to their CoP, and how teachers engaged in discussions during follow-on sessions. Based on the criterion established from experiences in year one and two, working with teachers of cohort 1 and cohort 2, the researchers finally selected four teams of eight teachers for the in-depth multiple case study portion of this research.

School	Locale Type of the School	Name (pseudonym)	Subject	Gender	Years of Teaching
HS #1	Rural	Corey Adams	Science	Female	13
		Mark Zion	ETE	Male	5
HS #2	Rural	Charlotte Ames	Science	Female	23
		John Johansen	ETE	Male	40
HS #3	Rural	Harold Crawford	ETE	Male	9
		Tina Kennedy	Science	Female	18
HS #4	Rural	Fae Knight	Science	Female	3
		Steven Dean	ETE	Male	19

Education Statistics classified the locale type of the schools as "City, Suburb, Town, Rural" (National Center for Education Statistics [NCES], n.d.). The database of Indiana School Referenda, which classified all Indiana schools' current locale types, was last updated in 2019 (Center for Evaluation, Policy, & Research [CEPR], 2019). HS # denotes high school number code for each participating school.

Table1. Description of Teacher Participants

Data Collection

Student Interviews. Students were interviewed in groups of two or three. Eight interview questions were crafted and pilot tested with a group of three students with similar characteristics to TRAILS participants to see if the interview questions were understood by high school students (Gay, Airasian, & Mills, 2011). Interview questions included both open-ended and closed questions based on Patton's (2015) six types of questions: a) experience and behavior questions; b) opinion and values questions; c) feeling questions; d) knowledge questions; e) sensory questions; and f) background/ demographic questions (see Appendix A).

Based on the interview questions, students were asked to provide more details as needed (semi-structured interviews). Each interview was completed in 10-15 minutes. A total of 17 science students and 17 ETE students were interviewed in groups of 2-3 students for each session. All thirteen interview sessions were video recorded and transcribed.

Student interview participants were selected by the teacher. The researchers instructed the teachers to select the participants based on criterion sampling (Gall, Gall, & Borg, 2007). Teachers selected each set of students using the following criteria: 1) demonstrated average performance during the lesson, 2) willingness to volunteer to participate in the interview session, and 3) submitted university internal review board (IRB) forms of parent and student consents (Sung, Kelley, & Han, 2019).

Two coders randomly selected 3 sessions from a total of 12 interview sessions (33.3%) and coded independently using the NVivo software to check reliability. Overall Kappa Coefficient was 0.6795, which indicates moderate level of agreement (McHugh, 2012).

Teacher Interviews. Teacher interviews were developed and implemented to better comprehend teachers' experiences and the meaning they had created from these experiences (Seidman, 1998). Individual phone interviews were conducted with the teachers in March 2017, a few months after the initial TRAILS implementation, and a second time during the 2018-2019 school year. The interviews were semi-structured, each lasting approximately 45 minutes (Mishler, 1986). The interview guide (See Appendix B) was developed based on a review of related literature (Pathak & Intratat, 2016; Wang, Moore, Roehrig, & Park, 2011) as well as data from pre-program interviews conducted with a school administrator and three teachers, not part of this project, who had recently participated in similar STEM initiatives. The purpose of the pre-program interviews was to identify challenges teachers could encounter and to incorporate knowledge gained from related projects into this program.

Observations. A total of 24 hours and 56 minutes of class observations within 37 classes (5 ETE classes, 5 Science classes, and 27 integrated classes) were conducted from September 28, 2018 to May 2, 2019 (See Appendix C). The researchers developed a class observation template, following the STEM class structure (See Appendix D). The observation template was pilot tested in a high school engineering classroom, with a teacher not participating in TRAILS. The teacher was selected because he teaches using a similar approach to TRAILS in a similar context of the participants in this study (Ruel, Wagner, & Gillespie, 2016). The researchers visited the classes as complete observers. Thus, the researchers did not engage in instruction or class discussions. All observations were recorded as artifacts (Appendix E), which were highly descriptive, including participants, setting, activities, and behaviors of the participants (Merriam & Tisdell, 2015). During observation data collection, the research assistant checked the accuracy of the template and confirmed the details of her teacher implementation report with each TRAILS teacher observed.

Teacher Reports. A teacher implementation report template was adapted from Merriam (1998) and compiled to align with the TRAILS integrated STEM approach. The researcher completed the teacher implementation report during each classroom observation (see Appendix D). Additionally, teachers were provided the template to complete for the entire TRAILS unit plan so teachers could indicate their approach to addressing key features of TRAILS which include a) develop biomimicry inspired design challenge to create 3D printed prototyped solutions and; b) engage students in engineering design, and science inquiry. The teacher implementation reports from class observations were cross-checked (member check) with the teacher of the class after each session for validity (Gay et al., 2011).

Curriculum materials and student samples. Curriculum materials and student samples were collected as artifacts for analysis. Teachers were asked to provide examples of students' work with low, medium, and high performance to provide a spectrum of student samples. These included: a) student samples of classroom project presentation slides, prototype test results, and engineer's notebook excerpts; b) student samples of 21st century rubric assessment results (Buck Institute for Education, 2013); and c) samples of students' 3D printed prototypes.

Teachers were asked to provide the description of the amount of time spent on each criterion (engineering design, science inquiry, and biomimicry) for all the lessons using the classroom observation template. The fourth feature of 3D printing (prototyping) was also captured in the template but was not compiled in the results since prototyping was not included in all classrooms (Appendix D).

Blogs and websites created by the teachers and students were reported to the research team, and photos were also collected to see how they scaffolded their knowledge through a variety of opportunities of STEM practices.

Data Analysis

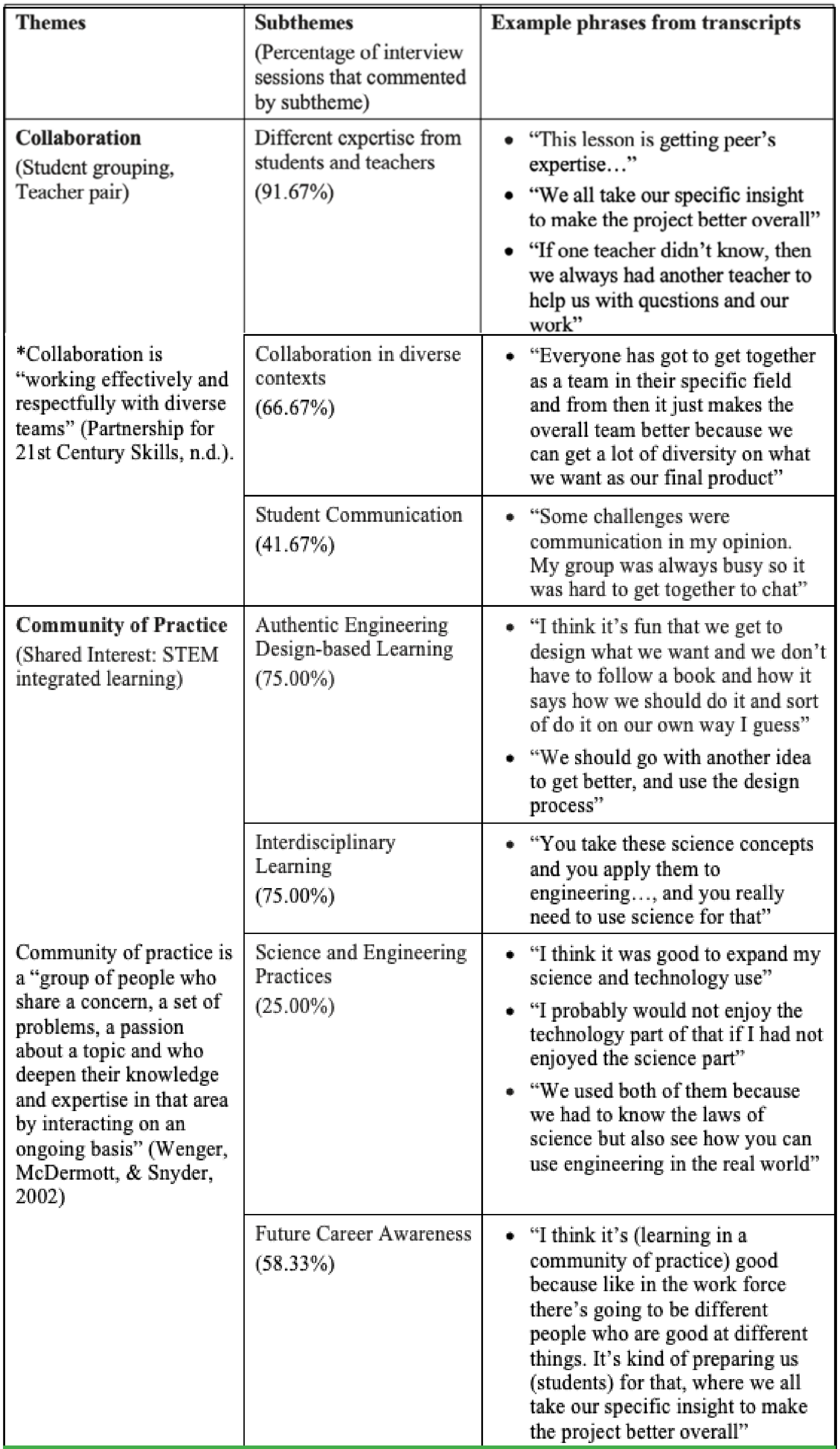
Internal validity (credibility), reliability (consistency), and generalizability (external validity, transferability) are concerns for the trustworthiness of qualitative research. To ensure internal validity and reliability of this qualitative research, triangulation was employed by using multiple sources of data, which included interviews, observations, reports, and documents. Interview data, which were collected from different researchers (AUTHORS #1, #2, #4) with different perspectives, follow up interviews with the same people and cross-checking the data collected from researchers (AUTHORS #1, #2, #3), were all used as triangulation for the strategies to enhance trustworthiness of the current qualitative research (Merriam & Tisdell, 2015; Merriam, 1998).

Member checks were also completed. On every observation, the observer recorded field notes and filled out the teacher implementation template, which can describe the STEM class structure; when possible the field notes and observation records were checked with the teacher who taught the lesson that day (Merriam & Tisdell, 2015; Merriam, 1998).

Results

Student Interviews

The data was reviewed by each researcher for validation of the codes and themes. Upon completion of the review of the transcripts, two major themes from student interviews emerged: (1) collaboration through student grouping and teacher pairing (2) community of practice through integrated STEM learning (Table 2) (Corbin & Strauss 2015; El Nagdi, Leammukda, & Roehrig, 2018).



Themes	**Subthemes** (Percentage of interview sessions that commented by subtheme)	**Example phrases from transcripts**
Collaboration (Student grouping, Teacher pair)	Different expertise from students and teachers (91.67%)	• "This lesson is getting peer's expertise…" • "We all take our specific insight to make the project better overall" • "If one teacher didn't know, then we always had another teacher to help us with questions and our work"
*Collaboration is "working effectively and respectfully with diverse teams" (Partnership for 21st Century Skills, n.d.).	Collaboration in diverse contexts (66.67%)	• "Everyone has got to get together as a team in their specific field and from then it just makes the overall team better because we can get a lot of diversity on what we want as our final product"
	Student Communication (41.67%)	• "Some challenges were communication in my opinion. My group was always busy so it was hard to get together to chat"
Community of Practice (Shared Interest: STEM integrated learning)	Authentic Engineering Design-based Learning (75.00%)	• "I think it's fun that we get to design what we want and we don't have to follow a book and how it says how we should do it and sort of do it on our own way I guess" • "We should go with another idea to get better, and use the design process"
	Interdisciplinary Learning (75.00%)	• "You take these science concepts and you apply them to engineering…, and you really need to use science for that"
Community of practice is a "group of people who share a concern, a set of problems, a passion about a topic and who deepen their knowledge and expertise in that area by interacting on an ongoing basis" (Wenger, McDermott, & Snyder, 2002)	Science and Engineering Practices (25.00%)	• "I think it was good to expand my science and technology use" • "I probably would not enjoy the technology part of that if I had not enjoyed the science part" • "We used both of them because we had to know the laws of science but also see how you can use engineering in the real world"
	Future Career Awareness (58.33%)	• "I think it's (learning in a community of practice) good because like in the work force there's going to be different people who are good at different things. It's kind of preparing us (students) for that, where we all take our specific insight to make the project better overall"

Table2. Themes and Subthemes Emerged from the Analysis of Student Interviews

Integrated STEM Student Collaboration. Integrated STEM student collaboration emerged as the most dominant theme of the student responses. Student collaboration was critical when pairing teachers of different expertise and requiring science and ETE students to work together. During the STEM integrated project, students developed designs together in teams, completed necessary project tasks, and solved problems together throughout the project. Some students said it was sometimes harder to work with students from other subjects. For example, they did not always share the same interests, which translated to some not being invested in the project as much as others and therefore taking fewer responsibilities. However, most students said it was a great experience being grouped with students from other disciplines and that they were able to solve the problems easier through collaborations. Students also said they benefited from collaborating with peers possessing different perspectives since different ideas and skills were necessary to improve the project. Interview results suggested that it was critical for the students of diverse expertise to work as an effective team. Students also said dividing tasks and coming together for the final product improved their vision and the overall design solution.

> *"There were a lot of different ranges of expertise [on the student teams], because we knew what we were doing with the design software [CAD] and we kind of showed them the different constraints we had with our software. They helped us with selecting a bug from a certain environment . . . pretty much the biology side of things . . . while we designed what they were giving us to develop a final product [biomimicry inspired fishing lure prototype]". (ETE student)*

> *"I liked the group work more than the individual tasks because I like talking and giving opinions and trying to make that into a better thing instead of just my own vision and my creation". (Science student)*

Community of practice. Community of practice arose as another major theme. Community of Practice is a "group of people who share a concern, a set of problems, a passion about a topic and who deepen their knowledge and expertise in that area by interacting on an ongoing basis" (Wenger, McDermott, & Snyder, 2002, p.4). Sub themes emerged including project and design-based learning, interdisciplinary learning, real-life applications, and future career awareness within the theme Community of Practice in the context of integrated STEM. Students said project-based and design-based learning enabled them to use the design process, which challenged their minds and allowed for better ideas. They said that the design project gave them instructions on how to do what they wanted and that it was enjoyable figuring out different methods instead of the generic way of learning. They said that the design process was a learning process since it was their own project to solve and that the design process stimulated their insights to improve the project overall. Students also demonstrated that design-based and interdisciplinary strategies of the integrated STEM project were linked to real-world applications.

> *"In my opinion, it's shedding new light on how to solve new problems and make things work better in the real world and not just in your imagination, you know. Thanks to science we can figure out the math to certain issues, and we get to study and figure out how to change things to be a better fit". (ETE student)*

> *"I liked it (interdisciplinary learning) because, like I said, you can't have engineering without biology or science. . . it helps you see how you can use engineering in the real world". (ETE student)*

Furthermore, students said design-based and interdisciplinary learning with peers from other discipline were helpful for their future careers and that they brought everything together during the design project which they say was necessary for their future jobs.

Teacher Interviews

All teacher interviews were conducted by researchers a few months after the initial lesson implementation within the first year of the project and a second time during the 2018-2019 school year. Data from the teacher interviews were reviewed by each researcher for validation of the codes and themes. Upon completion of the review of the transcripts, two major themes emerged from the teacher interviews: (1) the value of teacher collaboration and (2) the central role adaptability played as teachers implemented the curriculum (Table 3) (Corbin & Strauss, 2015).

First, researchers found that the teachers preferred collaboration to teaching an integrated STEM project alone. Additionally, when it was possible, co-teaching was the preferred approach when compared with sharing students. Using the co-teaching approach, teacher teams believed their students benefitted from having consistent access to two teachers with differing areas of expertise and that this approach made it easier to help students master content from multiple disciplines as well as increase STEM career awareness. Many also commented that cross-cutting concepts were more easily understood and applied when students were taught together. Additionally, course planning was easier when the teachers were in the same room teaching together.

One team of teachers had the opportunity to teach classes that met different times during the first year and at the same time during the second year. The differences they observed illustrate teachers' preference for co-teaching.

> *"Last year's group felt disjointed a bit and, in their minds,. . . we are just making something. This year, I get to have the conversations and point out to my kids . . . this is why we do certain things the way we do, and this*

Themes	**Subthemes** (Percentage of interview sessions that commented by subtheme)	**Example phrases from transcripts**
Collaboration Collaboration is "working effectively and respectfully with diverse teams" (Partnership for 21st Century Skills, n.d.).	Benefits to Students (81.25%)	• "Each set of kids is seeing what they have to bring to the table."
	Satisfying (81.25%)	• "To work with someone in science and collaborate has been great!" • "It's been so fun to work with Steven (pseudonym), (TRAILS partner teacher)."
	Extended Network (56.25%)	• "I would love to (collaborate) pull in math teachers, maybe physics teachers." • "I was an island (…in my teaching) and didn't work with others. Now it's very different."
Adaptability "A defining feature of teaching work is that it involves novelty, change, and uncertainty on a daily basis. Being able to respond effectively to this change is known as **adaptability**." (Collie & Martin, 2016, p.2).	Willingness to Adapt and to Fail (100%)	• "We are tweaking (our TRAILS lessons) every year." • "It (TRAILS lessons) has evolved and gotten much better." • "Neither of us have egos that make it have to be done one way or another."
	Learned New Material (43.75%)	• "I've had to learn lots of engineering, but it's made the class stronger."

Table3. Themes and Subthemes Emerged from the Analysis of Teacher Interviews

is how it works in the real world". (Mr. Crawford, HS#3)

There were challenges to teacher collaboration, including finding time to develop the curriculum together, but for each of the teachers, collaboration was a positive experience that led to new friendships and many enjoyable hours spent teaching together. For several teachers, this experience with collaboration also prompted them to pursue opportunities to work with other colleagues outside their discipline for other school initiatives.

A second subtheme that emerged was teacher adaptability. Teachers taught under a variety of circumstances, and some teacher pairs experienced quite different scenarios from year to year primarily due to differences in class scheduling. Generally, they were able to make the program work regardless of whether the paired courses were taught during the same period and regardless of which courses were used to implement the project. They also exhibited flexibility as they learned and taught cross-disciplinary material for their course and learned to fail at times and to let their students fail.

> *"I had to work TRAILS into my curriculum and ended up throwing out some of the electronics content that I'm supposed to teach because there is nothing in electronics curriculum about building bugs or 3D printing or parametric modeling. I've been teaching digital electronics for forever, 15 years. I know what content I can skip or cannot skip". (Mr. Dean, HS#4)*
>
> *"It's been a learning process for me. I have no engineering background. I have had to learn that part. Even learning the engineering design process is new for me. But within an environmental science class, it does play really well to do a real-world task. I've had to learn lots of engineering, but it's made the class stronger". (Ms. Knight, HS#4)*
>
> *To summarize these findings, the themes of teacher adaptability and the value of collaboration were woven throughout the teacher interviews.*

Observations

The following observation data will be presented by high school coded (HS#1 to HS#4) and summarized.

HS #1. The researchers made 5 observations that were each 50 minutes. All the TRAILS lessons including one exemplar lesson, D-BAIT, connect science inquiry (biomimicry) and engineering design. The exemplar lesson D-BAIT developed by the TRAILS team employed biomimicry concepts for designing the fishing lure that mimics the functions of aquatic insects. For the exemplar lesson (D-BAIT), science and engineering technology students were combined in one classroom. Most classes met within the media center at the school. This allowed both science and engineering technology students to learn and work together in the same space. The lessons involved basic biology and technology concepts necessary for the design challenge. Design teams were interdisciplinary, consisting of both science and engineering students. These teams design together, solved problems together, and redesigned together as needed. Only, the 3D printing of the prototype was done separately by the engineering students.

However, for the custom lesson, which the HS#1 teachers developed collaboratively with the research team during the summer PD, they used a different approach. The custom lesson, Bumblebot, involved the completion of various science inquiry and technology lessons, and students were given the engineering design challenge to design a robotic bee (non-flying) to solve pollination problems. Students from science class learned about pollination, dissected flowers, and researched details about the anatomy of bees, photosynthesis, and energy transfer. The science students shared some of this knowledge with the engineering students during brainstorming sessions. Engineering students learned how to create VEX robots, CAD and 3D printing skills, and mechanical design. Engineering students shared some of this knowledge with science students during design sessions.

HS #2. The researchers made 6 observations that were each 50 minutes and involved 8 total classes: 2 ETE classes, 3 science classes, and a joint meeting of all three classes (2 ETE classes and 1 science class). Science and engineering students were grouped and worked together for their design project throughout the lessons. Even though science and engineering students were not taught in the same room all the time, they met at least 1-2 times every week for collaboration, and both teachers shared the lesson plan, lesson schedule, and teaching materials. Also, they shared the students and taught the lessons collaboratively. Ms. Ames taught science concepts, and Mr. Johansen instructed the engineering part to both classes. As well as the exemplar lesson, D-BAIT, the custom lesson, Animal Armor, also infuses science inquiry (biomimicry) to the design project. The researchers observed the custom lesson, Animal Armor, which challenges students to identify and research insects then apply arthropods structures to their designs. Engineering and science students worked together to design removable bug parts to show the adaptations of the bugs between the different orders. Specifically, science students generated ideas and developed a design, and engineering students made a three-dimensional sketch and an isometric sketch with dimensions of the Animal Armor design.

On a joint meeting day, all 39 students from science and engineering classes were divided into two groups: one group worked with Ms. Ames while the other group was with Mr. Johansen. Ms. Ames taught the science part while Mr. Johansen taught engineering. After they completed their instructions, they switched classrooms and taught the same parts to the next group, which is a common cooperative learning approach to teaching (Moorehead & Grillo, 2013). Both groups of students interacted and communicated actively. Design briefs and decision matrices were used throughout the lesson for idea generation, and engineering students 3D printed prototypes while science students worked on presentation slides and trifold displays. For collaboration, engineering students taught the bio students basic 3D modeling and printing, and science students taught engineering students biology concepts. These teachers and students benefited greatly from having LGI (Large Group Instruction) room to use for this collaboration, and the classes met together at least once a week all school year.

HS #3. The teachers at this school taught three TRAILS lessons: D-BAIT, Clean Sweep, and Temporary Sanctuary. The researchers observed the D-BAIT lesson and the Clean Sweep lesson. Clean Sweep combined environmental issues, science inquiry, and engineering design through the designing of biomimicry inspired prototype that collects plastic pollution from an aquatic habitat.

Teachers, Mr. Crawford and Ms. Kennedy, taught all three lessons altogether in the same room. Each student group consists of 5-6 students, 2-3 engineering students, and 3-4 science students, with both group and individual work. The teachers observed that from the two years implementing the TRAILS lesson, students were increasingly more motivated and committed to the project during the second year of implementation. Communication between students, between students and teachers, and between teachers seemed critical for the success of this approach. From the HS #3 class observations, we identified that peer feedback was a key teacher strategy for this integrated STEM lesson by students checking each other's design and helping one another as needed. Supports from the school administration also seemed critical. When the research team visited the class again on presentation day, the superintendent, the principal, and the computer technology coordinator attended as audience members and showed their interests and support for the project.

HS #4. The lesson observed was a teacher custom lesson called Nature's Origami. We observed Nature's Origami lesson five times, 50 minutes each: two science classes, two engineering classes, and two classes of the joint meeting. The lesson was designed to teach alternative energy sources and basic circuit construction while students designed solar panel arrays that mimic natural folding functions. The two HS #4 teachers developed and planned the lessons collaboratively but taught separately. They had time for one joint meeting for each lesson, D-BAIT and Nature's Origami, and all the other classes were taught by each teacher.

When we observed Ms. Knight's science class, the students worked in small groups of three to four students. They discussed the prototype (the solar collector) using sketches and design matrix, and Ms. Knight distilled engineering concepts and processes into the science class in addition to science inquiry. Students were brainstorming and discussing the efficiency, durability, and size, which were related to the functions and measurements.

On a joint meeting day (both ETE and Science), the students were gathered in a science classroom, and both classes were grouped together. During the meeting, Mr. Dean taught electricity (solar panel), modification of the solar panel, and active solar systems. He also gave instructions on tools and electricity, which taught how to connect solar panels to electricity. Ms. Knight taught science inquiry, the natural folding function (biomimicry) that can be applied to the prototype design, and encouraged brainstorming. Due to the use of two separate classes for this project, a student resource time (joint meeting) was utilized as a time for collaboration.

All in all, the teachers within this team prioritized teaching their respective disciplines during the integrated STEM project although both teachers were the most comfortable at teaching outside their area and had the ability to do so.

Models of Integrated STEM Teaching Findings

The researchers will now provide a summary of the research results and then followed by further descriptions of the three models of implementation that answer the question: What models of integrated STEM teaching emerge from the teacher pairs during implementation? The research identified three models of implementation. Although model 1 was not used by teachers in this case study, this model is a typical approach by many teachers who seek to integrate STEM within their own classroom and do not have partnering teachers. The researchers call model 1: STEM Content Inclusion model. A second model that emerged from the research is called model 2: STEM Content Integration Model. The third model of implementation to emerge from the research was model 3: STEM Content and Practices Integration (Transdisciplinary Model).

Model 2 (STEM Content Integration Model) includes HS #4 for both D-BAIT and the custom lesson, Nature's Origami, and HS #1 for the custom lesson, Bumblebot. In model 2, teachers did not share students but collaborated between teachers and students when needed. Students from both classes met a couple of times throughout the lesson for collaboration.

Model 3 is the STEM Content and Practices Integration model (Transdisciplinary Model). In this model, the engineering teacher and science teacher shared their students and taught both classes together. HS #2 and HS #3 for both D-BAIT and custom lesson (Temporary Sanctuary) and HS #1 for D-BAIT lesson were included in this model. Figure 4 illustrates model 2, and figure 5 illustrates model 3.

Model 1	Model 2	Model 3
STEM Content Inclusion	**STEM Content Integration**	**STEM Content and Practices Integration**
• Content is integrated in one classroom	• Each domain teacher shared STEM content from domain	• Content and practices are shared within a community of practice
• One teacher adds one or more additional STEM domain content within the classroom	• Each domain teacher teaches content, equipping student to become experienced with key practices and knowledge	• STEM knowledge and practices inform process taken by students
• The approach is often called multidisciplinary	• Two or more STEM domains information and practices are shared across classrooms • Students become 'experts' sharing STEM knowledge	• For example, science inquiry, engineering design, and computational thinking are informed by the integration process (crosscutting)

Table 4. Three Models of Integrated STEM Implementation

Models of Integrated STEM Education

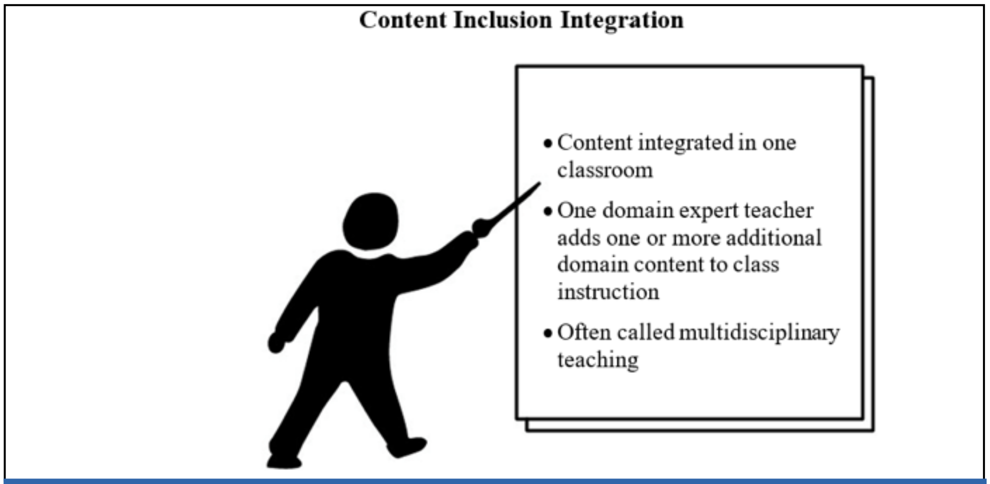
Table 4 presents a summary of the three models of implementation that emerged within the TRAILS project. This summary provides details about the unique features of each model.

STEM Content Inclusion model

The first integrated STEM model of implementation that emerged within the TRAILS project but did not occur within these cases presented here was the Inclusion Integrated STEM model. In the inclusion model, STEM subjects are integrated within one classroom. The teacher using the inclusion model integrates additional STEM content with the STEM content from his or her domain. For example, a science teacher might purposely integrate mathematics into their course content. Teaching instruction from an integrated STEM approach requires purposeful integration. Although any subject within STEM likely cannot be taught without the other domains, integrated STEM instruction requires careful and purposeful instruction to add the additional content, make cross-cutting connections, and enhancing learning both subjects in an authentic approach and application. The inclusion model is often the first step for teachers to take to approach integrated STEM teaching. STEM teachers may not have access to other teachers outside their domain or lack opportunities to co-teach with another teacher, so their only option is the inclusion model. It is important to note that the inclusion model is not an inferior model of integrated STEM, however, as the additional models are presented, there are benefits from other models that an inclusion integrated model instructor may not experience because he or she must teach alone. An obvious example of the inclusion model would be teachers teaching in the primary and intermediate grades. These teachers often have no choice but to teach from an inclusion integrated STEM model. Primary and intermediate grade teachers are called upon to be an expert in all disciplines. Although this can be an overwhelming responsibility, these teachers are also advantaged to implement new approaches to teaching because they are often in charge of their own instruction, although they are bound by standards and high stakes testing.

STEM Content Integration Model

The second model of integration that emerged from the TRAILS program research can be best described as STEM Content Integration. We define the STEM Content



- Content integrated in one classroom
- One domain expert teacher adds one or more additional domain content to class instruction
- Often called multidisciplinary teaching

Figure1. Content Inclusion Integration Model

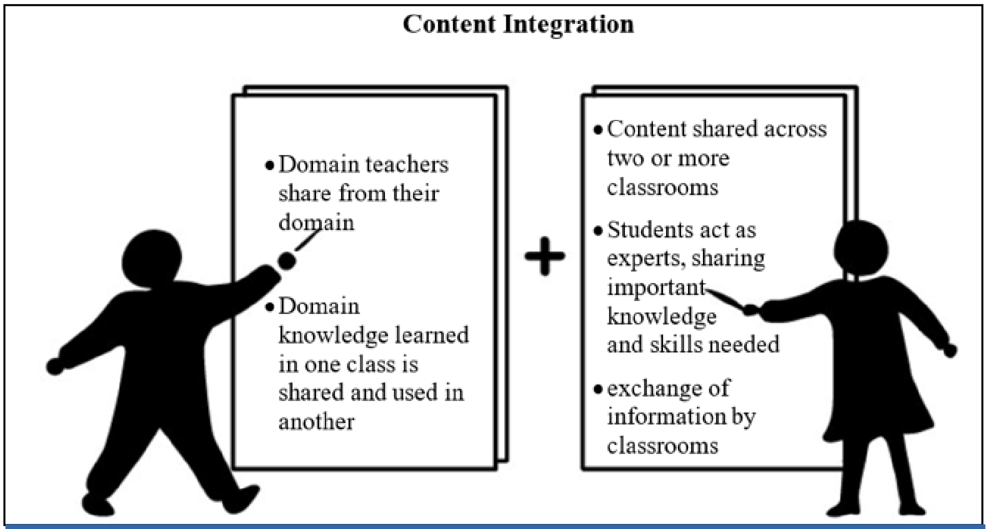


Figure 2. STEM Content Integration Model

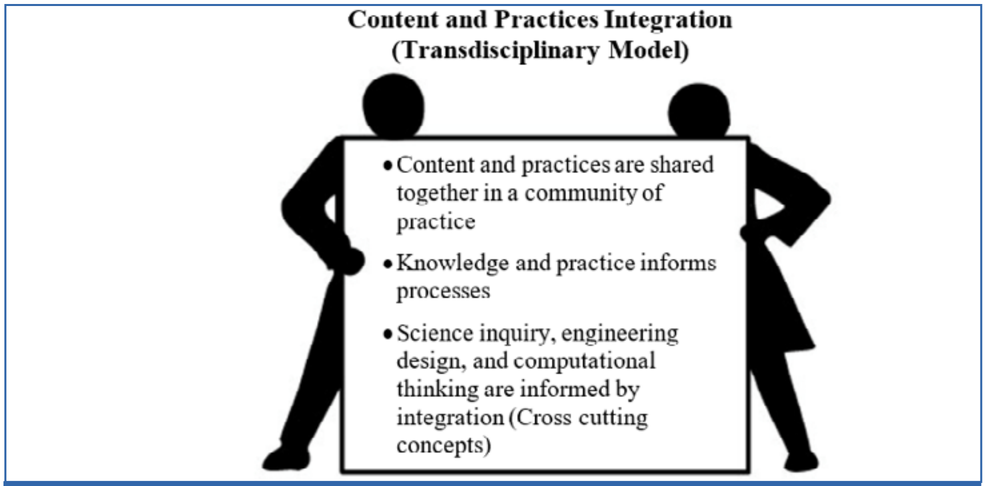


Figure 3. STEM Content and Practices Integration: Transdisciplinary Model

Integration model as the approach to integrated STEM when one domain teacher shares their domain knowledge with their students and requires that their students share this knowledge with another partnering classroom. Again, the domain knowledge is purposefully integrated into lessons and is shared with students to be used on their own and with another classroom. Additionally, students from both classrooms are called upon to share this knowledge learned and exchange this knowledge and skills as content experts. For example, in the TRAILS project both science and engineering technology teachers using the content integration model taught their students and challenged them to share this knowledge and skills with students from the other partnering classroom.

The catalyst of this integration for the TRAILS project is the engineering design challenge that requires authentic integration of knowledge and skills from two or more domains. These engineering design challenges used a biomimicry approach that requires students to learn biology, environmental, and or other life sciences in order to create a biomimicry design. Additionally, the TRAILS project required students to create 3D printed prototype solutions by leveraging the technology students' knowledge and expertise in using parametric modeling software (CAD).

STEM Content and Practices Integration (Transdisciplinary Model)

The third model of integration that emerged from the TRAILS program research is called STEM Content and Practices Integration. This model is similar to the content integration model, but this approach is not an exchange of knowledge and skills; rather, this model shares practices and knowledge. Some suggest this is a team-teaching model of implementing STEM education (El Nagdi et al., 2018). TRAILS teachers using this model collaborated between two classrooms, sharing experiences in such a way that technology students were participating in science inquiry experiences alongside the science students. Science students engaged in engineering design experiences alongside technology students. Technology students learned to ask questions, collect biological samples, carry out investigations, and make observations and inferences, (Science and Engineering Practices). Science students engaged in designing solutions by brainstorming sessions, benchmarking existing solutions, and using numerical data to develop final design decisions. Science students assist technology students as they create CAD models for 3D printing and collaborate to make adjustments and redesigns when needed. The teacher from the 2nd classroom also shares his or her knowledge with their students as well as with the students from the first classroom. Some have discovered that student achievement increases using this approach to teaching when teachers collaborate and build a learning community (Fulton & Britton, 2011).

Features of TRAILS Implementation

To answer the research questions, What were the features of the intervention (TRAILS program) that were implemented in the classroom? and What features of the intervention were emphasized?, the researchers provided TRAILS teacher implementation report template for the teachers to complete for the entire TRAILS unit plan so they could indicate their levels of implementation of the three key features of the TRAILS program. Lesson implementation descriptions provided by the teachers were converted to charts to compare time management (see figure 4 and figure 5).

Each teacher pair submitted two teacher implementation reports for the D-BAIT lesson and custom lesson which reflect how much time they spent on three features: a) science inquiry; b) biomimicry; and c) engineering design. Another key feature included in the template was prototyping; however, since prototyping did not occur in some science classrooms, this feature could not be charted (supplemental file 2). For example, For HS #2, both engineering and science classes did the project together and shared the same time on science inquiry, engineering design, and biomimicry, but only the engineering class spent time for 3D printing (prototyping). For HS #3, they all shared all three domains and prototyping occurred in both classrooms. For HS #1, the engineering class spent additional time for 3D printing.

Student STEM Knowledge Test

For the research question, How do the three models compared as measured by students' STEM knowledge test results? (2.a.), the researchers further investigated the effect of three different instructional strategies on students' STEM knowledge achievement by analyzing the knowledge test of the exemplar lesson, D-BAIT, of all TRAILS students. Students took the pre and posttest before and after the D-BAIT lesson. Like the D-BAIT lesson, The D-BAIT knowledge test was developed by the research team (Kelley, Knowles, Sung, & Han, under review). The test consists of 20 questions with five subject domains: biomimicry, engineering design, physics, entomology, and food web. Internal-consistency reliability of the D-BAIT knowledge test was measured by the research

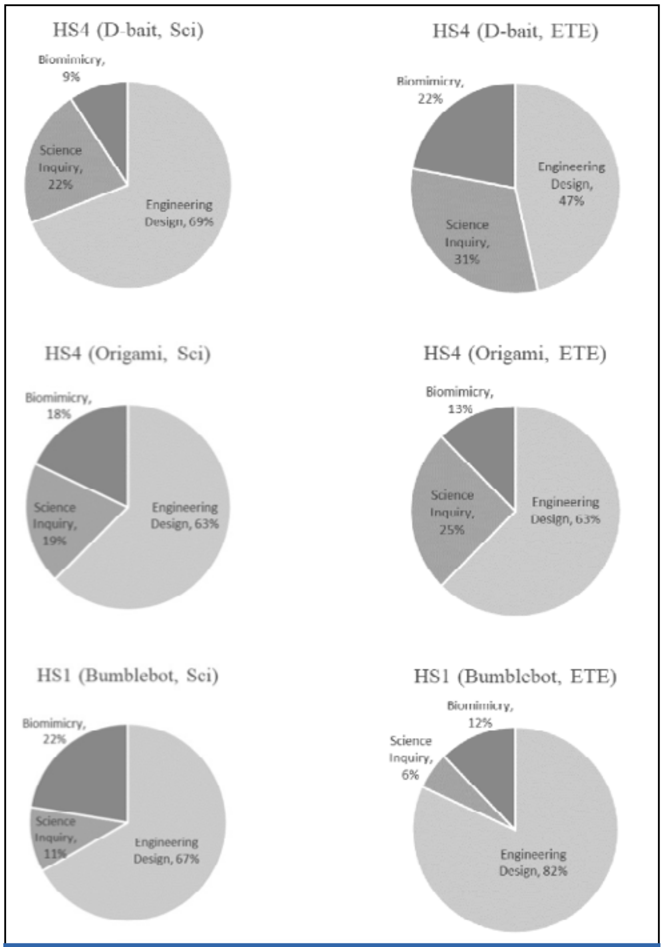
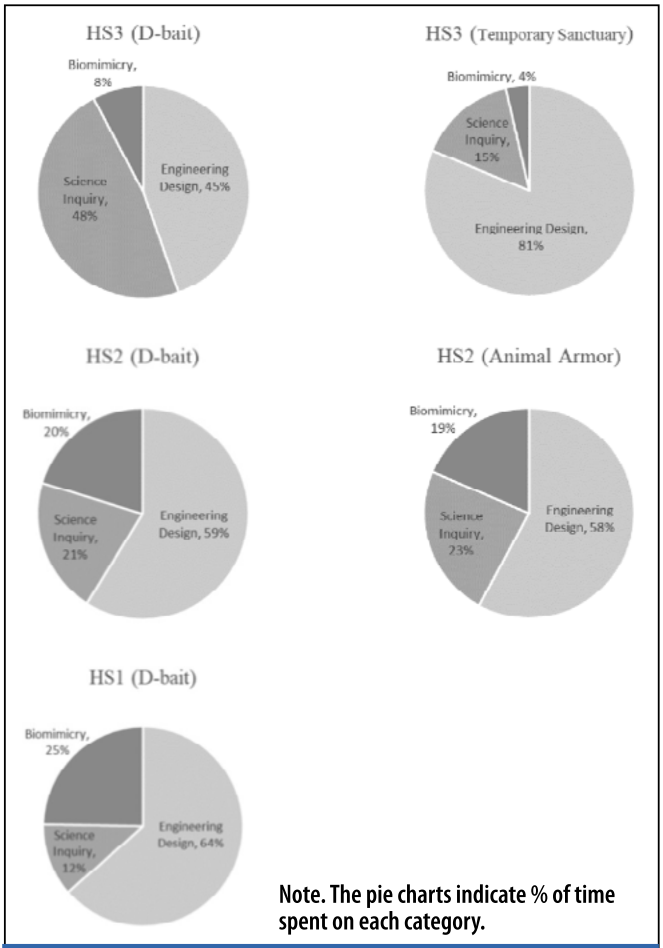


Figure 4. STEM Content Integration Model (Model 2)



Note. The pie charts indicate % of time spent on each category.

Figure 5. STEM Content and Practices Integration (Transdisciplinary Model) (Model 3)

team, and the overall Cronbach's Alpha score was over 0.7.

Table 5 shows the demographics of the students who submitted IRB parent and student consent forms and took both pre and posttest before and after they learned the D-BAIT lesson.

Students data were divided into three groups depending on the instructional strategies they learned. All three groups (Model 1, 2, 3) increased their knowledge test scores from pre to posttest (see Table 6). Although Model 1 was not observed within the case-study portion of this research, several TRAILS teachers used the inclusion model to deliver the integrated STEM lessons, often because their teacher partner drop out of the TRAILS program. However, the single TRAILS teachers still remained committed to the project and implemented all features of the program within his or her own classroom.

To test if there was a difference between groups in their score increases, an analysis of variance test (ANOVA) was conducted. From the preliminary inspection of the data, the researchers confirmed that there was homogeneity of variances in the three models (Levene statistic = 0.117, $p = 0.890$). The ANOVA test result shows that there is a significant difference between groups in their score increases ($F(2, 710) = 6.744$, $p = 0.001$) (Table 7). Mean score increase of model 2 and model 3 were significantly higher than model 1 ($p = 0.003$ and $p < 0.001$ respectively). However, difference between model 2 and model 3 was not significant ($p = 0.250$) (see Table 8).

The results indicate that teacher collaborations, represented in model 2 and 3, were more effective in increasing student knowledge test scores than model 1, teachers teaching integrated STEM alone in a single classroom.

Gender		Ethnicity					Sum
Male	Female	White	Black	Hispanic	Asian	Other	
446 (62.6%)	267 (37.4%)	607 (85.1%)	24 (3.4%)	54 (7.6%)	19 (2.7%)	9 (1.2%)	713 (100%)

Note. The students, who did not submit IRB consent forms, were excluded from the final data collection.

Table 5. Student Data Collection (2016-2019)

	N	Mean Score Increase	Standard Deviation	Standard Error
Model 1	149	0.70	3.040	0.249
Model 2	347	1.55	2.855	0.153
Model 3	217	1.81	2.941	0.200
Total	713	1.45	2.944	0.110

Table 6. Mean Score Increase from Pre to Post D-BAIT STEM Knowledge Test

	Sum of Squares	df	Mean Square	F	Significance
Between Groups	155.537	2	57.768	6.744	**0.001**
Within Groups	6055.044	710	8.528		
Total	6170.581	712			

Table 7. ANOVA Test Result

(I) Model	(J) Model	Mean Difference (I-J)	Standard Error	Significance
1	**2**	-0.855*	0.286	**0.003**
	3	-1.108*	0.311	**0.000**
2	1	0.855*	0.286	0.003
	3	-0.253	0.253	0.317
3	1	1.108*	0.311	0.000
	2	0.253	0.253	0.317

Note. Model 1 vs. Model 2,3: significant (* p<0.05). Model 2 vs. Model 3: not significant.

Table 8. Multiple Comparison (Post-Hoc Test: Fisher's Least Significant Difference [LSD])

Discussion and Conclusion

Education policymakers, school officials, and indeed, the U.S. global workforce possess high expectations for the promise of integrated STEM education K-12. For that promise to become a reality, STEM education research must continue to investigate pedagogical approaches that work and those approaches that can overcome barriers that exist within the current educational structure. The full promise of integrated STEM education can only be realized in the typical school classroom and not limited to magnet or charter STEM schools. Furthermore, to write the full story of success will likely only come from STEM teachers that are brave enough to overcome barriers to experience the benefits of STEM integration.

TRAILS leadership team identified a problem; there was no protocol to determine the best approach to STEM lesson implementation. Teachers participating in the project struggled to plan for integrated STEM lessons due to many constraints impeding their ability to deliver these lessons using an integrated approach. The constraints facing these teachers are noted above: overcrowded curriculum, high stakes testing, limited planning time, inconsistent schedules, and even classroom location with science and technology wings on opposite ends of the school campus. The TRAILS team realized they could not overcome all of the constraints for the science and engineering technology teachers, so they challenged the teachers to develop their own approach to implementing integrated STEM as how content is taught and integrated often varies from teacher to teacher and school to school (Brown, R., Brown, J., Reardon, & Merrill, 2011; Bybee, 2013; Johnson, 2012; Vasquez, Sneider, & Comer, 2013). Additionally, teachers were challenged to ensure inclusion of the following features for TRAILS lessons development and implementation:

A) develop biomimicry inspired design challenge to create 3D printed prototyped solutions;
b) engage students in engineering design and science inquiry;
C) leverage a community of practice;
D) promote 21st century skills requiring students to collaborate in design teams.

Each of these features was essential to achieve the goals of TRAILS. However, teachers were provided autonomy regarding how they would implement the integrated STEM lessons; offering an opportunity to customize an implementation plan that would work at their school with their students as well as establishing the best approach to work with their partnering teacher. Forcing a prescribed approach to integrated STEM would likely have failed. Instead, by using this approach to training the teachers, many teams left the professional development empowered and motivated to implement the TRAILS lessons. Furthermore, some teachers became advocates for changing school structure by seeking assistance from building principals or school scheduling staff in order to change teaching schedules, thus, alleviating conflicts for students in the science and technology classrooms.

This study sought to capture experiences from some of these teachers and their students in order to better describe models of integrated STEM implementation. Three models that emerged from this study are as follows:

a) Content Inclusion Integration Model;
b) STEM Content Integration Model; and
c) STEM Content and Practices Integration: Transdisciplinary Model.

Although each model has benefits and limits, it is essential to realize that each school and each teacher must determine what approach is best for their students and can fit their school structure. This research has revealed benefits in model three due to multiple achieved outcomes such as addressing crosscutting concepts, learning authentic approaches to science and engineering design, and helping students make connections between learned STEM practices linked to STEM careers. The authors have seen how much time a dedication it takes to implement a level three model and recognized that most teachers and schools do not start at a level 3 model. Furthermore, it is essential to note that many teachers must begin at model 1 and progress to model 3. This case study research just focused on understanding how teachers implement an integrated STEM approach to teaching and not focus on the impact on student learning or teacher professional development. However, it is important to note other studies within TRAILS have focused on the impact on student learning and teacher growth during professional development (Kelley, Knowles, Holland, & Han, 2020) and findings indicate benefits using these approaches to integrated STEM. (All TRAILS lessons and materials can be downloaded from TRAILS official website, https://www.purdue.edu/trails/).

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