Journal of Science Education and Technology (2020) 29:499–518
https://doi.org/10.1007/s10956-020-09832-w

STEAM Designed and Enacted: Understanding the Process of Design and Implementation of STEAM Curriculum in an Elementary School

Cassie F. Quigley[1] · Dani Herro[2] · Elizabeth King[3] · Holly Plank[4]

Published online: 15 May 2020

Abstract

Educators are now moving classroom instructional objectives away from *what content do we need to know* towards *how can we support learners in the process of inquiry.* Consequently, an increasing number of schools have revamped their curricula to support students. One such example of modified curricula is the rising trend of STEAM Education. However, limited research exists on STEAM teaching practices. The purpose of this study is to understand the ways in which elementary teachers can both design and enact STEAM teaching practices in order to define specific curricular supports for STEAM education. Our key findings were (1) teachers who designed relevant problems provided instructional pathways aligned to the STEAM conceptual model and (2) teacher facilitation promoted both inquiry and authentic tasks—two strategies often difficult for teachers. This research demonstrates the importance of teachers designing STEAM curriculum using problem-based units in ways that promote student inquiry. The data demonstrates this as critical to enact discipline integration, teacher facilitation, and authentic tasks.

Keywords STEAM · Curriculum design · Implementation · Elementary education

Introduction

Over the last two decades, educators have seen policies, committees, and new standards in the USA calling for a "new approach" to STEM education (National Research Council 1996, 2000). Central to these calls is a pedagogical shift from focusing on supporting the acquisition of content to promoting deeper learning by engaging students in inquiry, making, and creative technologies (Halverson 2005). From a practical perspective, this shift is driven by the growing disparity between the education provided in schools and the needs and interests of the children who will occupy future citizenry—citizens that can produce, create, and interact with a variety of technologies and knowledge types. From a pedagogical perspective this requires shifting instructional approaches, which involves creating curriculum that utilizes creative technologies and teaching strategies that embed content in inquiry-based learning wherein students are able to understand the content, see the value in the content, and transfer the content to new situations (Noguera et al. 2015).

Consistent with this way of thinking, educators are shifting didactic, lecture-based instructional modes to more participatory models where students are collaboratively engaged in the process of inquiry, making, and creative technologies (Squire 2007). As a result, educators are now moving classroom instructional objectives away from *what content do we need to know* towards *how can we support learners in the process of inquiry.* Consequently, an increasing number of schools have modified their curricula to support students. One such example of altered curricula is the rising trend of STEAM Education (Johnson et al. 2014). Existing STEAM education research has been focused on the conceptualization of STEAM (Quigley and Herro 2016, 2017; Sanders 2006), the understanding of the transdisciplinary nature of STEAM (Guyotte et al. 2015), the ways it can engage girls and students of color (Peppler and Bender 2013; Tsurusaki et al. 2017), and the integration of art and technology into other disciplines (Ko et al. 2012; Peppler and Bender 2013). Less research exists on the impact of STEAM instruction on students (Bush and

✉ Cassie F. Quigley
cquigley@pitt.edu

1 University of Pittsburgh, 5517 WW Posvar Hall, Pittsburgh, PA 15231, USA

2 Digital Media and Learning, Clemson University, Clemson, SC, USA

3 Educational Foundations, University of Wisconsin- Whitewater, Whitewater, WI, USA

4 Learning Sciences and Policy, University of Pittsburgh, Pittsburgh, PA, USA

Cook 2016). Few studies examine the role teachers play in designing and implementing STEAM curricula. However, curricular reforms are ultimately implemented by teachers, as Kim and Bolger (2017) discovered regarding STEAM education; if teachers lack knowledge, confidence, and curricular supports to implement change, that change is unlikely to occur. Therefore, the purpose of this study is to understand the ways in which elementary teachers can both design and enact STEAM teaching practices in order to define specific curricular supports for STEAM education. Our research question is: How do K-5 teachers design and implement STEAM learning environments?

Teacher Involvement in Curricular Design

As educators shift from content-focused curriculum towards more relevant, authentic experiences, they need support and often ask for sample instructional units and assessments (NGSS Lead States 2013). That said, it is widely understood that when teachers are left out of the design process, curriculum is not implemented effectively or at all (Kim and Bolger 2017). However, there is specific expertise needed for curricular design including generic design and process expertise and specific design expertise (Huizinga et al. 2014). The former entails the knowledge and skills needed to engage in the design process while the latter includes knowledge and skills needed to develop curriculum itself. The knowledge teachers need is multifaceted involving curriculum design expertise, subject matter knowledge, pedagogical content knowledge, and curriculum consistency expertise, with skills such as idea generation skills, material selection skills, systematic curriculum design skills, and implementation management skills. Without these skills, teachers often face challenges in both design and implementation of new curriculum. Huizinga et al. (2014) found that one way to mitigate challenges is to offer support that is just-in-time and context-specific. McFadden and Roehrig (2017) found it crucial that teachers are supported in the process of breaking free from past ways of developing curriculum, which leads to more fidelity in implementation. Similarly, Binkhorst et al. (2017) found that the more ownership a teacher perceives, the more likely they are to actually use the designed material in their classes. However, they call for more research into particular reform movements that can track design-to-implementation of the practices.

STEAM Instructional Practices Literature Review

While the notion of STEAM is widespread in fields such as design, architecture, and even engineering education, there is little empirical research regarding how to implement STEAM practices in K-12 settings. Additionally, K-12 educators have narrow conceptual understandings of how to design or teach using STEAM educational practices due to the limited research (Henriksen et al. 2016). This often results in teachers using existing STEM practices and attempting to "add on" the arts or humanities instead of integrating arts into the design and planning processes (Henriksen et al. 2016). With the concept of STEAM education in K-12 settings relatively new, this present study is informed by the literature detailing available approaches and strategies towards STEAM teaching. Specifically, we review the major themes that researchers discuss when examining STEAM education: discipline integration, problem-based learning, technology integration, and arts integration. These approaches assume that teachers can or should design learning environments with appropriate instructional activities promoting STEAM skills.

Discipline Integration

Discipline integration involves different content and methods of various fields to teach curricular concepts and solve complex problems. STEAM education often touts a transdisciplinary approach (Bush and Cook 2016; Quigley et al. 2017). Research on the notion of discipline integration has resulted in a variety of opinions of what transdisciplinary teaching is and what it requires (Kaufman et al. 2003). Transdisciplinary perspectives seek a balanced relationship among the various disciplines-meaning that one discipline does not take priority over the other. Meeth (1978) writes, "Transdisciplinary programs start with the issue or problem and, through the process of problem-solving, bring to bear the knowledge of those disciplines that contributes to a solution or resolution" (p. 10). The notion of transdisciplinary is in essence "beyond the disciplines." Transdisciplinary approaches use the collective expertise from many disciplines to pose and solve problems in a manner which foregrounds the problem, not the discipline. Most research cites that transdisciplinary approaches are the most difficult to teach given the traditional organizational structure of schools by subject area. This challenge requires supporting teachers in ways that approach learning from a transdisciplinary standpoint from the beginning of the instructional design process. In this way, students move beyond one correct way to solve a problem, towards an approach that integrates different solutions and perspectives.

Problem-Based Learning

Problem-based approaches are not new; they have been successfully implemented in classrooms for decades to help situate practical experiences or provide experiential learning in contexts understandable to youth (Hmelo-Silver 2004; Savery and Duffy 1995).

Studies examining the impact of problem-based learning report high levels of student engagement, an ability to think critically and solve problems, and a capacity to encourage student collaboration (Brush and Saye 2008; Penuel and Means 2000). In terms of STEAM teaching, problem-based learning was present in most of the reviewed studies of K-12 education. Typically, in school settings, the STEAM-focused studies demonstrated that problem-based learning was a part of the curricular approach (Margot and Kettler 2019; Shernoff et al. 2017) while in out-of-school settings or classroom “STEAM electives,” the focus was on a specific challenge or product for students to design or create (Perignat and Katz-Buonincontro 2019). This demonstrates that in K-12 settings, problem-based learning and STEAM seem in alignment, and often involve removing some restraints common in traditional school settings.

Technology Integration

Technology integration in STEAM instruction has been closely connected to the maker movement in K-12 as it is thought to encourage design thinking, creativity, STEM, and social skills (Cohen 2017). Makerspaces are considered “informal sites for creative production in art, science, and engineering where people of all ages blend digital and physical technologies to explore ideas, learn technical skills and new products” as a means to build, improve and share collective knowledge (Sheridan et al. 2014). In schools, they have been used as social and cognitive activities that lend themselves naturally to STEAM instruction, such as playfully making stories, honing computer science and literacy skills (Bull et al. 2017), engineering prosthetic limbs (Cook et al. 2015), creating prototypes as solutions to pollution (Kitagawa et al. 2018) and even making buttons, memory shirts and movie montages for bereavement (Seymour 2016). In STEAM units, technology-enabled making or sharing is part of the problem-solving process (Author in review). The benefit of the maker movement to increase design and engineering practices in K-12 classrooms. The connection between making and design and engineering practices has studied in recent years and with findings suggesting making aligns most closely with STEM and STEAM initiatives in schools (Taylor 2016). The research implies that opportunities for making, with technology integration, should be integrated in STEAM problem-solving.

Arts Integration

Perhaps the most misunderstood and misaligned component of STEAM teaching is arts integration, with the “A” representing both arts and humanities (Fountain 2014). Historically, the boundaries between art and science and music and math are fluid and encourage educators to exemplify breaking the rigid boundaries between the disciplines by engaging learners in creative and artistic ways to solve problems (Henrikson et al. 2016). Henrikson et al. provide examples in which teachers use visual arts to demonstrate understanding of a science concept, music, theater, or kinesthetic movement to explore a phenomenon. These authors discuss the complexity of knowledge production when students engage in “creative synthesis” where senses, prior experience, and new understandings produce new knowledge. They provide examples demonstrating the depth of understanding that can occur when learning in multisensory ways, such as an experienced swimmer exploring the physics of ocean waves, tides, and currents using prior experience, senses, and additional knowledge to create new meaning. Compared with the infrequent summarization of concepts in science, math, or literature, the arts offer opportunities for more creative synthesis of knowledge. Still, art is often only integrated through the design process, an important component of visual art. However, when this is the only level of art integration, students are not able to understand how art and engineering are different (Nathan et al. 2011). Students must understand that designers create artwork mostly for clients and that artists create expressive artwork to explore an issue, express an emotion, or to demonstrate a creative skill (Cross 2001). Although we recognize arts integration beyond design can often be difficult for content area teachers to integrate, we want to underscore its importance. In general, the transdisciplinary nature of STEAM teaching aligns with the nonlinear problem-solving and open-endedness of creative thinking (Mishra and Kereluik 2011), fostering a space for students to use their imagination, which fuels problem-solving (Eisner 2002).

STEAM Conceptual Model

Integrating the arts and humanities with STEM is essential for innovation as it provides an engaging and collaborative way to view the world, strengthening the connection between math and science in real-world applications (Wynn and Harris 2012). Further, STEAM teaching draws on a transdisciplinary approach which foregrounds the problem to be solved, versus a discipline-specific approach. Yet, many schools implement this new curricular innovation without a clear conceptualization of what STEAM is, how it differs from STEM, and what it looks like in classrooms. To support schools during this shift, we developed a conceptual model (see Fig. 1) to guide effective instructional practices for teachers to implement STEAM-based curricula using a previous a 3-year study of teachers (for details see Quigley and Herro 2017). The conceptual model is based on connected learning theory which posits that educators should value the ways youth are already engaged in learning across multiple disciplines and spaces; it suggests that the most effective learning environments draw on individual interest and social support to overcome adversity and

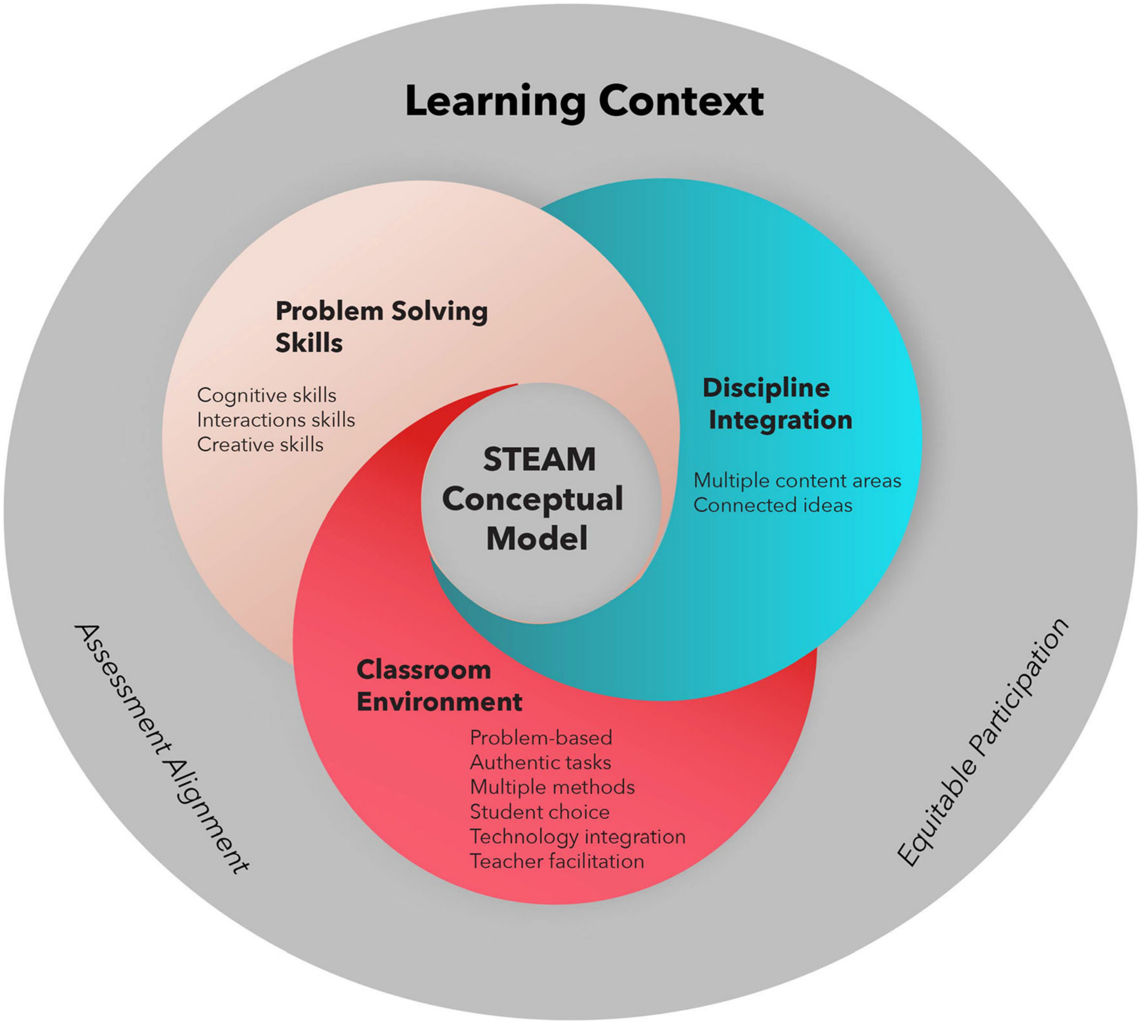

Fig. 1 STEAM conceptual model

acknowledge contributions (Ito et al. 2013). Connected learning theory guides STEAM instruction in two primary ways: (1) as a means to draw on students' interest in choosing relevant, real-world problems to solve when designing STEAM problem-solving scenarios (e.g., issues they care about and can relate to with a STEAM focus), and (2) providing technology options in which students participate readily outside of school such as video production, game design, robotics, digital drawing/sketching and connecting with peers to share creative solutions to problems (Grimes and Fields 2012).

The first dimension, *discipline integration*, is the way in which teachers connect multiple disciplines or content areas through a problem-based unit. While the model posits the goal of STEAM as transdisciplinary, the model also looks at variances of discipline integration (single content, multiple disciplines, and transdisciplinary). Our research found teachers were more readily able to integrate multiple disciplines when they aligned the disciplines to the problem to be solved. Therefore, the attributes in this dimension can be defined as multiple content areas and connected ideas. In classrooms with a high level of discipline integration, the content selection draws on different disciplines during problem-solving by using expert knowledge (e.g., community experts such as a local park ranger or landscape architect), multiple sources of information, and a variety of concepts or methods.

The second dimension, *classroom environment*, examines the ways in which teachers structure the classroom environment to facilitate problem-solving. This dimension includes a problem-based approach, authentic tasks, multiple ways to solve the problem, student choice, technology integration, and teacher facilitation. When teachers situate the task in a real-world event, it helps to make the problem and the content more relevant to the students. This dimension significantly informs practices teachers focus on during the creation and enactment of STEAM curricula. The classroom environment is purposely designed to recognize unique skills of diverse groups (i.e. minoritized students).

The third dimension, *problem-solving skills*, involves the ways in which teachers support the development of students' cognitive, interactive, and creative skills through a variety of instructional activities. These skills provide students with the means to solve problems. During STEAM lessons, teachers support students in the development of higher-order skills, such as abstracting, analyzing, applying, formulating, collaborating, and interpreting; constructing explanations; engaging in argumentation; disseminating evidence; and presenting. The conceptual model looks for teachers to regularly provide opportunities for students to practice these skills across contexts while encouraging students to explore multiple paths to solving a problem, which provides favorable conditions for sparking creative skills. These creative skills rely on a teacher's ability to offer concepts, tools, and experiences in open-ended, problem- solving scenarios. This model helps teachers design problem-solving tasks and classroom environments to promote student-guided learning that relies on peer support and collaboration. In this manner, our STEAM conceptual model is more than just a simple combination of science, technology, engineering, arts, and math content; it defines an instructional approach by which teachers inculcate a transdisciplinary perspective on real-world problems. Table 1 provides an example of a STEAM scenario and the learning context of the classroom environment, discipline integration, and problem-solving skills.

This unit was developed by Authors 1 and 2 and used during a professional development with the teachers to provide an example of a STEAM unit. The teachers were led through the unit as students, taking different lines of inquiry to explore the problem. The full unit was aligned to content area standards including developing solutions in maker activities. These activities included creating murals of lake life, designing and engineering a new hook or fishing to device, developing digital activity books to educate people on the threats fish face, designing video games in visual coding game-design software to detail the safe way to catch and release, and programming simple robots to mimic a fish life cycle (see Table 2). Community experts from the Great Lakes Bioenergy Research Center assisted teachers and their students in gathering credible information and answering questions.

Methods

We conducted a qualitative research study utilizing coding schemes (Saldaña 2015) based on the STEAM observational rubric (see Appendix) to understand how teachers designed and enacted this new curriculum to answer the following research question: How do K-5 teachers design and implement STEAM learning environments?

Table 1 Example STEAM problem: learning context applied to a specific scenario in the Midwest

Scenario	
Fishing is a tradition that is a part of many cultures, races, and ages. There are many famous stories built upon this pastime—Hemingway's *The Old Man* and Sea and *Herman Melville's* Moby Dick to name just a few. Not to mention the folklore that is a much of a part of the fishing culture as is the actual act. Cannot you just hear a fisherman telling you the size of the fish say, "It was *THIS* big" with arms stretched out? But as we have overfished our oceans and lakes, this pastime might actually become something of the past. About 1/3 of our oceans are at risk of being overfished. Smarter regulations are a part of that solution. One practice that is often used in Lake Mendota is "catch and release." This practice requires fishermen and women to release the fish back into the water. But, even with this practice 60% of the fish still die. The DNR is curious if there are ways that people could catch fish but allow for a "catch and release" that does not harm fish. The DNR is curious if youth could help them determine some of the challenges of "catch and release" and what some solutions are to this problem. Once you decide on the area of focus for the challenge (i.e., lack of understanding of the practice, fish being harmed by hooks, keeping the fish outside of the water) and solution for this challenge, you will design an educational tool that will help the public understand this change in practice.	Classroom environment: This scenario is problem-based, situated around a problem to solve regarding threats to fish with authentic tasks mimicking what happens in the real world. It is contemporary problem that is relevant to students' lives (near their homes on the Wisconsin lakeshore). Discipline integration: This scenario includes multiple content areas (science, technology, engineering design, social studies/humanities), and encourages multiple ways to solve the problem. The approach is transdisciplinary as it begins with the problem to solve vs. the disciplines; there is synthesis across disciplines related to the problem. Problem-solving skills: This scenario supports cognitive skills (analyzing and interpreting data; modeling) and interactional skills when presenting data in the form of the educational tool. Collaboration skills are utilized during problem-solving facilitated by technology that might include using Google Docs, Forms, Drawing, Presentations, and co-created iMovie or Adobe Spark videos to facilitate CPS.

Table 2 Example STEAM-aligned making activities (fishing scenario)

Example activity	Creative technology
Students model the safest way to catch and release the fish back to the lake.	Finch (programmable robot)
Students create informational and interactive posters using copper tape and stick on LEDs documenting potential harm to fish during the catch and release.	Chibitronics (paper circuits)
Students create sensor-supported new fishing hooks that would prevent harm to the fish	LittleBits (building block circuits, can be combined with craft-based materials)
Students collect air particulate data to make a case for how long certain species of fish should be out of the water.	Filtrete (air quality monitor)
Students create a diorama that models a safe practices for "catch and release" using a Visual Programmer to program sensors, servo motors, and LED arrays. Students can engineer solutions to one of the threats faced to the fish, for example mechanisms for capturing fish w/o use of hooks	Hummingbird Robotics Kit(programmable creative robotics kit)

Context

The K-5 elementary school is in a growing community in Southeastern Wisconsin. The area has a large refugee population (increased from 8 to 18% in 2019) and the district administrators were interested in curricular innovations that engaged students in deeper learning and fostered a sense of community. The school administration and teachers chose STEAM because of interest in problem-based learning, discipline integration, and engaging students. Fifty-seven percent of students receive free or reduced lunch. The demographics of the school are as follows: Racial/Ethnic background: Asian—7%; Black—25%; Hispanic—15%; White—40%; 2 or more races—13%. The school has 420 students, 25 classroom teachers, one principal, one assistant principal, an instructional coach, five special area teachers, and four support staff. At the time of this study, grades 3–5 had 1:1 daily Chromebook access. Grades K-2 had access to iPads regularly but did not have 1:1 access. The teachers participated in a four-day summer STEAM professional development (PD) program led by Authors 1 and 2. Details of this PD can be found in Quigley and Herro 2016. During this program, the teachers began creating a STEAM problem scenario and unit plan to be completed in early fall for feedback from Authors 1 and 2. This feedback was aligned to the STEAM principles and focused on concrete suggestions and providing resources in the form of specific technology suggestions, curricular resources, or websites with relevant information to the teachers. The unit plans were intentionally planned with adequate time so the teachers could receive the feedback with one-month planning time for the teachers to adjust the lessons. The instructional coach met with the team to review the feedback and to provide supports with how to make adjustments to the designed units. In October, Authors 1 and 2 observed the teachers implementing the planned lessons after each observation there was a feedback session in which Authors 1, 2, and the instructional coach provided support in the areas outlined in the rubric (problem-based, discipline integration, authentic tasks, teacher facilitation, inquiry, technology integration, and student choice). The spring units were implemented in March. The teachers submitted their unit plans to Authors 1 and 2 in January for feedback and classroom observations with the same feedback protocol as the fall.

Participants

Twenty-three classroom teachers and one instructional coach signed IRB consent forms representing each grade level at the school, except second grade who chose not to participate. Teachers worked in teaching teams within their grade levels during the PD and while creating STEAM unit plans. The teaching teams consisted of 4–5 teachers per grade level. All of the grade level teams designed the units together. At times, some of the grade levels (Grades 1, 3, and 5) paired up and team-taught.

Data Sources

The data sources were unit plans, reflections, classroom observations, and field notes. Each source is described in detail below.

Unit Plans

Each grade level team (K, 1, 3, 4, 5) designed two STEAM units ranging from 2 to 6 weeks of instruction time, depending on the topic. Unit plans included the following components: STEAM problem scenario, driving question, daily activities, standards, formative assessments, summative assessment, technology integration, and experts/community members.

Reflections on Implementing Units

Each teacher completed an online reflection after their implementation of the STEAM unit. The reflections included four

Table 3 Data codes from STEAM rubric for design and enactment by grade level

Grade level	STEAM scenario topic	Design	Enactment
K	Fall How to make healthy choices (sleep, exercise, food) Spring How to help injured animals	Fall *Problem-based:* Situated around the students' lives. Problem was making healthy choices in the cafeteria, how much sleep they need for their age, how to get the most out of recess, and similar choices. *Inquiry:* No opportunities students to investigate their ideas related to the problem. *Discipline integration*: The content literacy and math-focused instead of integrating according to the problem *Authentic tasks*: Tasks included read-aloud, and opportunities for counting steps. Opportunities remain to connect the tasks to the problem (collecting data to see number of steps over time vs. one-time activity). *Teacher facilitation:* The plan mentioned having children brainstorm ideas about ways to stay healthy and a KWL chart was used in the lesson observed. The designed lesson is very teacher directed *Technology integration:* Pedometers and SMART board. Opportunities exist for even young learners to produce technology. *Student choice:* includes a topic within the larger problem to examine. Unclear of the method that students will use to do this. Spring *Problem-based:* Connected to local place (within the XX County Humane Society, which is local and relevant). *Inquiry:* The driving question is connected to the problem and broad - so it promotes inquiry. The content includes animals, nature, experts from the local community and a number of books with topics connected to solving the problem. *Inquiry:* *Discipline integration:* There are science, SS, speaking and listening, engineering, math, and ELA standards included that should naturally integrate the disciplines. *Authentic Tasks:* *Teacher facilitation:* the unit plan includes a lot of teacher-led activities. *Student choice:* does suggest a lot of inquiry in terms of choice of animals and an open-ended problem for students to investigate and then produce (choices) of final products. *Technology integration:* Minimal besides videos and connections to teacher instruction.	Fall *Problem-based:* The teacher repeatedly refers to the problem of healthy eating, exercise, and mindfulness, which helps to provide clear objectives. *Inquiry:* There was inquiry in a brainstorming activity related to how students' exercise (in the gym, at school, you can do push-ups etc.). *Discipline integration:* This lesson focused on math of counting and watching a video on healthy choices. *Teacher facilitation:* The lesson was teacher directed. The teacher was positioned in the front of the room and the students were seated on the carpet for most of the lesson. *Technology integration:* Students used the pedometers but were told exactly what to do and all counted the exact same steps (from room to bathroom). *Student choice*: There is not student choice for how to approach problem-solving. Spring *Problem-based:* Injured (and healthy) animals are of high interest to the students; the animal also has a small animal hospital Objectives were clear, students are taking a nature walk and counting tallies. *Inquiry:* There is a lot of inquiry during the walk that demonstrates connected ideas (should we pick up candy wrappers so the birds do not choke on it? Do you know what we do not see any rabbits today?). There could have been more explicit connections to the ideas in the scenario. The lesson had one solution and one method (once inside). *Discipline integration:* Science, math and ELA are naturally connected to the problem. There is less focus on engineering. Students are also drawing pictures and reading about animals. Math (counting, graphing, tallying), science (animal habitats and habits, nature), ELA (writing sentences, reading, drawing pictures of what they saw. *Authentic Tasks:* The teacher follows up with a graphing activity connected to the problem. Students can articulate what they are doing and are providing information about birds, squirrels, rabbits and a neighborhood dog. Students are attempting to analyze their graphs but struggling. They do not fully understand the tallies and graphing keys *Teacher facilitation:* The teacher is making connections for what they saw as a whole-class activity (directed). *Student choice:* There is limited student choice in this lesson. *Technology integration:* Students would have benefited from using manipulatives to graph.
1	Fall Disappearance of bees Spring Food waste in the cafeteria	Fall *Problem-based:* The scenario is based on a problem around the extinction of bees and helping the public understand the importance of bees. *Inquiry:* There are multiple ways to solve the problem based on the different guided topics such as the importance of bees in our food systems, environment, or causes of the declining bee populations.	Fall *Problem-based:* The problem is introduced and referred to many times during the lesson. The tasks are well-aligned to understanding the importance that bees play in the food chain and finding a way to protect them. Bees are local/relevant to kids at the school and the issue is global (authentic task). *Inquiry:* The students were working on researching their topics (solutions, causes, etc.)

Table 3 (continued)

Grade level	STEAM scenario topic	Design	Enactment
		Discipline integration: The unit plan outlines life cycles and food webs for science, building a model of a bee for engineering, introducing hexagons in math, in art the student will create a bee dance and a school wall mural project. *Teacher facilitation:* The plan discussed inquiry opportunities such as creating food packages that support bee populations, small group work around honeybee hives but much of the planned work is teacher directed (whole group activities led by the teacher) *Student choice:* the type of bee to investigate, choice of partner, choice of products *Technology Integration:* Video creation of the bee dance, use of storykit for bee books, Layar for AR creation Spring *Problem-based:* Scenario discussed food waste from a global and local perspective *Inquiry:* The inquiry was directed through demos and class investigations *Discipline integration:* Social studies discusses human changes to the environment and developing an opinion about an issue in your school or community. Science included communicating solutions to reduce the impact of humans on the land, water, air. *Teacher facilitation:* Much of the planned lessons were directed by the teacher including whole-class discussions and activities. *Student choice:* The unit plan discusses an opportunity to research a topic related to environmental awareness but this did not appear in the lesson plans *Technology integration:* In this form of e-books and watching videos. No creative technology opportunities for students	*Discipline integration:* Many references to math, science and engineering throughout the lesson. Students used their "bee book" to organize learning and complete a chart of traits for drones, queen bee and worker bees. They are also categorizing and comparing bees. *Teacher facilitation:* Teacher facilitation was strong. Co-teaching appears to work very well for the two teachers. They are comfortable facilitating and walking from group-to-group. Students are taught group facilitation skills as well. The teachers encourage the students to make mistakes and help one another; they circulate around the room. *Student choice:* The students were working in their groups on their different chosen topics *Technology Integration:* Not apparent in this lesson Spring *Problem-based*: The students are aware of the problem to be solved and the problem is posted on the wall. *Inquiry:* There is a disconnect between the problem scenario and the lessons which are broader. This lesson was about technology use in the classroom which is connected to environmental action but unconnected to the specific problem. As a result, the teacher is asking most of the questions and directing the learning. *Discipline integration*: Present in the plans, but this lesson was a directed class about technology use *Teacher facilitation:* Not student centered. *Student choice*: Little choice. *Technology integration*: Instructional technology
3	Fall Developing a park that accommodates and attracts people, plants, and animals to the park Spring Awareness of increasing extreme weather conditions	Fall *Problem-based:* The scenario is situated in a real-world problem about growth of their home town and disappearing green space. The students created a plan for a new park for the city council to consider *Inquiry:* The unit plan noted that students will be able to research the benefits of the current park and the importance of the open spaces as well as come up with designs that will better attract people while still protecting the ecosystems present. *Discipline integration:* The unit plan discussed science as ecosystems of a prairie. Social studies included negative effects on environment from human interactions, engineering included designing a park, arts included creating an audio file of the sounds of the park, ELA included a persuasive essay. *Teacher facilitation:* The unit plan described teacher-directed plans including specific page numbers from textbooks. Some of the lesson were more student directed such as the map creation and designing their presentations *Student choice:* choice in map creation and how they present their ideas *Technology integration:* Students created Adobe Spark presentation Spring *Problem-based:* The scenario is based on increasing extreme weather conditions and how to ensure the citizens are informed *Inquiry:* Students are brainstorming ideas, asking new questions, writing and sharing their questions and using them for research	Fall *Problem-based:* Scenario grounded in problem but the teachers did not refer back to the problem during this lesson. *Inquiry:* While the unit plan noted this would happen through student-driven questioning, the observed lesson did not do this. The students were reading passages and answering questions. *Discipline integration:* This lesson was focused on ELA *Teacher facilitation:* Instruction was largely led by the teacher. *Student choice:* Not present in this lesson *Technology Integration*: Not present in this lesson. Spring *Problem-based:* The scenario is most definitely problem based as they are asking students to investigate, understand and share the impact they have on the environment and it's a relationship to climate change. The driving question poses 2 problems for them to find solutions for. However, the students were confused how the expert could help them solve the problem posed to them. *Inquiry:* Some inquiry is present as the students created a list of questions for the expert *Discipline integration*: The expert discussed use of a variety of disciplines in their job and the importance of using different ideas to solve problems.

Table 3 (continued)

Grade level	STEAM scenario topic	Design	Enactment
		Discipline integration: science included making a claim about the merit of a design solution that reduces the impacts of a weather-related hazard. Math incorporated a scaled picture and bar graph. ELA includes conduct a short research project that builds knowledge on a topic. Engineering includes building a solution for the flooding. Arts included options for the final project and a focus on design *Teacher facilitation:* The unit plan incorporated a high level of student-directed lessons including partnering and brainstorming and grouping according to student interest. Student choice: There is a menu of options for the final project *Technology integration*: Students created google Sheets, infographics, video creation for the final project	Teacher facilitation: the teacher is directing most of the lesson, the students are interacting very little with one another and just a few are asking (or even allowed to ask) the experts questions *Student choice:* Not present in this lesson *Technology integration:* Not present in this lesson
4	Fall Creation of a community center Spring Hearing damage and ways to reduce the negative impacts of sound	Fall *Problem-based:* The scenario was creating a design for a shared community space that is accessible, energy-efficient and valuable to the youth in the community. *Inquiry*: narrowly focused on asking questions of expert but also determining which energy source to choose *Discipline integration*: Math incorporated area and perimeter formulas and measurement, ELA included opinion writing, science was related to energy and fuels, social studies included forming a political argument. *Teacher facilitation:* At times narrowly, teacher directed such as textbook reading, defining terms. However, when the design portion began, it shifted to student-directed learning *Student choice*: design of the community center, energy source, features of the center *Technology Integration*: Room designer, google maps, creating a looping video of the features of the community center Spring *Problem-based*: The scenario is built around a child with hearing loss and ways to make it relevant to all children I*nquiry*: Students are able to investigate a topic related to their interest and follow it through the entire project. *Discipline integration*: Science is related to understanding sound as a wave, Social studies empathizing with others, engineering designing new types of hearing aids or protection for ears, Arts creating a musical instrument *Teacher facilitation*: Students are grouped by interest across classrooms and this directs most of the unit plan outside a few directed lessons. Student choice: Final project, topics, and the ways in which they investigate the problem *Technology integration*: using Lego WeDo and video creation. Google Docs for the planning stages	Fall *Problem-based:* The lesson was connected to the problem of study but students need more clarity and reminders about how this is used in the solving the problem. *Inquiry*: While the overall question of study is inquiry-rich there was little opportunity beyond research type (where to look for information) for inquiry. The students had a lot of great questions which could be used for spring boarding into inquiry. These were largely ignored by the teachers. *Discipline integration:* This class was focused on a writing prompt of "what kind of energy should we use for our community center and why?" and did not integrate disciplines outside of science and ELA. *Teacher facilitation:* Varied across teachers. Most were very directed. *Student choice:* Not present in this lesson *Technology Integration:* Smartboard were used so it was from an instructional standpoint vs. students directing the use of tech Spring *Problem-based*: This is problem based and relevent to their lives. They also built in a number of problems to solve "nested' in the scenario—e.g., using Legos to create sound waves, having them consider problems from an empathetic standpoint to suggest solutions, and you have some great math problems to solve in terms of decibels. *Inquiry*: This is a strength of the unit. The students are able to ask questions throughout related to noise levels in a variety of environments. *Discipline integration*: Teacher is asking the students what they will need to solve the problem and their answers look different. Promotion of ideas that the problems will be solved different ways. *Teacher facilitation*: Students are divided by interest groups. They ask a lot of questions and coming up with potential solutions already (some are implausible). The lesson provides many avenues for inquiry. The students drove the topic as well as the methods and materials. At the end the students would be engaged in safety, design, education, etc. *Student choice*: There is so much student choice in this project. They can choose to express their learning through a poster, poem, game, or presentation—or a combination of them.

Table 3 (continued)

Grade level	STEAM scenario topic	Design	Enactment
			Technology integration: Google classroom and docs used for organization. Some students are using google draw for their models.
5	Fall School cafeteria re-design Spring Water quality and increase in population growth	Fall *Problem-based:* Connected to a real-world problem at the school related to the cafeteria. *Discipline integration:* The driving question was: How can we improve the cafeteria experience at XX Elementary school? This provided opportunities for connecting ideas and multiple disciplines including research in ELA as well as persuasive writing, engineering design in terms of the new layout for the cafeteria, noise reduction, science with healthy choices, math using budgeting and %. *Authentic tasks:* the unit plan is detailed with ideas about the hook and daily activities which helps to connect ideas and thinking about authentically connecting the disciplines. *Student choice and inquiry:* Students chose a topic to investigate (food, space, use, logistics, etc.) as well as the way to disseminate their results *Teacher facilitation:* Students are grouped by interest across classrooms and this directs most of the unit plan outside a few directed lessons *Technology integration:* Students used Google Docs collaboratively for planning, Google Draw, movie making, poster creation, or infograms for final products. Spring *Problem-based:* While the problem of increased population is a real-world problem, the unit plan demonstrated a challenge with connecting population growth and water quality; this could be a concern for students developing an understanding of what water quality is. *Discipline integration:* The water problem is only partially connected to population growth. Reading about the water cycle but little connection its relationship to the problem. There was mention of arts integration in the water barrels. Engineering design could use further development. *Authentic tasks:* the scenario and driving question is related to population growth in the area and issues with the water system. *Technology integration:* Students will create presentations for their final products.	Fall *Problem-based:* The teacher referenced the problem scenario and students discussed the problem with high interest. *Authentic tasks:* Students brainstormed questions to ask their expert (head of district's cafeteria food menu) and goals for the expert and the questions asked were clearly connected and across the content areas. *Discipline integration:* Student-driven topics ranged from food safety, waste, financial concerns, nutrition, and access, they asked questions about student choice, culture awareness etc. This was clearly not an add-on to instruction but folded into curriculum. *Student choice and inquiry:* During debriefing the teachers noted how (after the fieldtrip to a local tech hub—an engaging topic), the students were taking this topic to another level and could integrate more content areas than originally planned *Teacher facilitation:* Students are divided by interest groups. The students led the direction of the unit through these interest groups, which allowed the lessons to follow the students' interests. *Technology integration*: Students were readily collaborating using Google Docs Spring *Problem-based:* This problem was locally relevant but there is a concern about engagement. It is clear the teachers understand the students and constructed the scenario from this standpoint, however the enactment does not represent this context *Discipline integration:* In this lesson, there is little discipline integration, students were reciting facts about clouds *Authentic tasks and inquiry:* The teacher is trying to connect the ideas for the students, more inquiry would help to make some of the connections. This lesson is very discussion based, completed whole group for the first portion of the lesson, then individually *Teacher facilitation:* Few opportunities for teacher facilitation as the goal was to learn some facts from the articles. *Technology integration:*

short answer questions about implementation successes and challenges, areas of needed support, and the design process. An example question was, "During planning for the second unit, how did you approach this process? Was it different from the first time you did unit planning?"

Classroom Observations

Each grade level was observed at least twice during the academic year while implementing the two STEAM units. The researchers used an observational rubric to guide their observations which included the three dimensions of STEAM as described above (Appendix). This rubric was designed based on the conceptual model outlined in this paper (Quigley and Herro 2016), and modified based on research of implementation (Quigley and Herro 2019). It has been used by the research team for the past 5 years to support teachers during STEAM implementation.

Field Notes from Debriefing Sessions Post Observation

Author 3 took field notes documenting the conversations about support and feedback on observations. The debriefing sessions took place in person, the same day as the observations.

Data Analysis

To determine the extent to which the teachers designed units based on STEAM principles, Authors 1, 2, and 3 independently analyzed the unit plans using the codes from STEAM instructional approaches (problem-based, discipline integration, authentic tasks, teacher facilitation, inquiry, technology integration, and student choice). As a part of this analysis, the authors examined all of the components of the unit plans to determine how well the units aligned to the principles. Each author noted the extent to which the codes (e.g., student choice) were included and made notes about the type inclusion. Author 1 made comparisons across the codes noting differences. The interrater reliability was 89%. Then, the authors met to discuss differences. Infrequently, the researchers tagged the data with multiple codes when more than one component of STEAM was evident. Thus, the authors coded all observation notes and reviewed every coding difference to reach consensus. During the coding discussions, the boundaries and definitions of the codes were defined and refined. This data is represented in Table 3. The same procedure was repeated for the implementation stage of the study through the use of the observational rubrics (Appendix) and fieldnotes to determine if the designed curriculum was implemented. Then we utilized the reflections from the teachers as secondary data sources to further explore the process of designing and implementing this new curriculum. The data presented in Table 3 provides examples of each of the principles.

Results

Using the STEAM principles as codes for the data, Table 3 provides a comparison of design and enacted practices of each of the principles (problem-based, inquiry, discipline integration, authentic tasks, teacher facilitation, technology integration, and student choice). The first column is the grade level, the second column is the scenario topic, the third column is the coded data from the unit plans, and the fourth column is the coded data from the observational rubric and feedback sessions.

In this section, we provide a summary and description of the data by grade level to demonstrate the differences and alignment in STEAM principles throughout the classrooms. The codes are italicized throughout this section.

Kindergarten

For the kindergarten teaching team, across both fall and spring semesters, designing *a problem-based* unit was an area of strength. The teaching team was able to design a unit that incorporated a problem that offered opportunities for student inquiry (how to make healthy choices in the spring and how to help injured animals in the fall). In essence, the designed curriculum included opportunities for *problem-based*, *authentically designed tasks*, which incorporated *student choice*, *and multiple disciplines*. As they implemented the units, we observed challenges in moving from teacher-directed tasks towards *facilitation* as the biggest impediment to promoting STEAM in their classroom; this was also confirmed by the teachers during post-observation discussions. The kindergarten teachers regularly relied on teacher-directed instruction where the teacher relied on asking questions and waiting for one student to respond with an answer. This approach, while it generated student responses, rarely led to the enactment of inquiry where students were able to test their ideas. However, the spring unit began with a teacher-led nature walk that encouraged questioning by the students and provided a platform that fostered *inquiry*. Still, in their kindergarten classrooms, the designed and enacted STEAM curriculum was primarily focused on math and literacy skills that were disconnected to the problem-solving. For example, the teachers used a planned timed reading and small group reading instruction as a part of STEAM instead of integrating relevant reading or literacy skills into the STEAM lessons. During the debrief, the teachers noted that they "felt constrained by district-mandated curriculum," despite the instructional coach and principal encouraging the teachers to focus on the STEAM conceptual model in an authentic way using the STEAM instructional strategies while utilizing the other portion of the day for the prescribed curriculum.

Grade 1

Both the fall and spring unit plans incorporated *relevant problems* for the students to solve. In the fall, the students researched a topic related to the disappearance of the bees such as pesticide, lack of habitat, sound pollution, etc. The teachers also created a "bee book" which helped to *facilitate* student learning, providing checkpoints for teacher feedback and guidance on the requirements of the final project. Additionally, the teachers cotaught the lessons with their students in one classroom and pointed to this as being a strategy to help support teacher facilitation. *Discipline integration* was present in both fall and spring. In the fall, this integration was evident as the teachers referenced math, science, and engineering throughout the lesson. However, in the spring, the teacher directed their focus on e-waste (discarded technology products) using lecturing techniques and providing little acknowledgement of multiple disciplines to solve the problem. *Technology integration* was planned (video creation, and book creation), but limited in enactment. Interestingly, the spring unit included *problem-based* components, but *inquiry* was much more directed through teacher demonstrations and investigations pre-planned by the teacher that used guided, whole-class discussions. In the spring, *creative technology* was also absent in the plans and only instructional technology was enacted. The implementation mimicked the designed curriculum in that there was little opportunity for student-directed learning. Additionally, there was a disconnect between the designed problem around food waste and the implemented curriculum which were around the topics of waste in general.

Grade 3

In the fall, the designed curriculum included a *problem-based* unit around park development in the local area that included opportunities *for student-directed inquiry*, engaging with *multiple disciplines*, *choice in map creation*, and *creative technologies* through the use of Adobe Spark. The fall unit was broader, focusing on awareness of extreme weather. This broad question led to confusion for the students in how the tasks (such as engaging with a scientist who studies in Antarctica) might connect to their lives in Wisconsin. During the spring, the problem scenario around extreme weather also provided opportunities for *inquiry* in investigations, discipline integration, and a high level of student-direct learning including formation of student collaborative groups based on research topic. There was a *menu of options* (student choice) for the final assessment focused on creative technologies such as video creation. During the enactment, in the fall, the teachers relied on activities that were more *teacher-directed* such as reading passages and answering questions. In the spring, the teachers noted that they were focused on bringing in *multiple disciplines* and they did this through a variety of experts visiting the classroom. The students helped to brainstorm questions for the experts and were engaged in the conversation but the students had difficulty connecting the experts to the specific problem that they were solving.

Grade 4

The Grade 4 team designed *problem-based* units in both fall and spring. The fall unit had fewer opportunities for inquiry in that the *inquiry* centered on deciding which energy source should power the community-based center they were designing. In the spring, *inquiry* guided every aspect of the unit. The students brainstormed ideas related to their problem of hearing loss in teens. In terms of *teacher facilitation*, the students were grouped (across all grade 4 classrooms) by their ideas, which included creating sound-canceling headphones, researching building insulators, and finding ways to reduce noise pollution. The *students chose* the methods, materials, and the way they would disseminate this information in terms of presentation. The teacher asked the students what they needed to solve the problem and their answers looked different, as they promoted the ideas that the problems could be solved different ways (*inquiry). Creative technologies* were used to encourage designing models and prototyping, and this was apparent in the students' work.

Grade 5

In the fall unit, the problem scenario promoted *inquiry* and authentic tasks around re-designing the school cafeteria. Students engaged in a variety of investigations related to their line of inquiry pointing to the ability to solve the problem in different ways as well as an opportunity to promote *student inquiry.* In this way, the relevant problem laid the groundwork to enact *student inquiry.* However, in the spring a problem that addressed issues with local water quality was less connected to students' interest. This created a challenge once it was enacted. During the spring observation and in the post-observation debrief, we noted that it was difficult for teachers to create authentic tasks related to the problem. They discussed frustration with the problem, saying that it originally appeared to be *problem-based* but lacked relevance and connection to students' lives. They noted the students were interested in the overall problem they presented, but the teachers failed to develop tasks that engaged the students. In the fall, grade five was able to seamlessly incorporate Google Docs as a brainstorming tool, and the teachers noted this supported *student inquiry* in ways they had not originally conceptualized. The students were able to brainstorm ideas online and group themselves according to areas of interest (food, space, utility, etc.). Grade five was able to *integrate the discipline* authentically in the fall, however, in the spring, the designed curriculum did not allow for *discipline integration* because of the way the problem was being conceptualized around water quality. While the topic could incorporate *discipline integration*, this was not present in the implementation. This points to the importance of both the design of the problem scenario and instructional approaches which support authentic learning that is interesting to students.

Discussion

This discussion provides a synthesis of the results with a focus on how the STEAM principles are interrelated. In this way, we do not provide another discussion of the principles but rather the relationship between the principles. Our key findings were 1) teachers who designed relevant problems provided instructional pathways aligned to the STEAM conceptual model, and 2) teacher facilitation promoted both inquiry and authentic tasks- two strategies often difficult for teachers. Finally, we discuss how integration of technology and disciplines provides opportunities for authentic assessments and student choice.

Relevant Problems Promoted Alignment of the STEAM Conceptual Model

Relevancy is dependent on the context of the students in each classroom. Therefore, the ways in which the teachers design units to make STEAM relevant varies depending on the students they teach. There are useful strategies, particular to grade levels, gleaned from this research to guide other teachers.

Across the grade levels, when teachers focused on relevancy during the design, the alignment to the other components of STEAM was more evident in both the design and enactment. Being able to create a problem scenario connected to student lives was critical to promote these instructional practices but it was not an easy task for the teachers. As noted, at times teachers would develop a relevant unit but then they struggled to do so consistently. The teachers noted that the students found that the topic was interesting, and they were engaged during the discussion with the expert, but the teachers noted the students struggled making connections to their local environment. To better support the teachers, future professional development was targeted on design thinking and how students empathize with the problems in order to help students in making connections between their lives and the problems (Köppen and Meinel 2015). Specifically, we worked with the teachers to consider how they could introduce the STEAM problem to include an activity that helped students consider the ways the problem impacted their life.

For STEAM education, during the design phase of the planning process, it is necessary to model and support ways for teachers to help students understand relevancy. This could include surveying students, whole-class discussions that gauge reaction to community issues, or brainstorming sessions. Determining if problem scenarios will be relevant to their students' lives can ensure that teachers find interesting, relevant, or even more specific problems, so students, in turn, see how tasks aligned to the scenario are authentic to the problem. This implies that teachers need dedicated time with coaches or colleagues to create a relevant problem, allowing opportunities for drafting ideas, providing feedback and making revisions, and additional supports if the unit does not engage students. McFadden and Roehrig (2017) describe this support as continuous design supports that reinforce teachers throughout the entire process and helps to prevent teachers from resorting back to their previous curriculum or ways of teaching.

Teacher Facilitation Promoted Inquiry and Authentic Tasks

Aligned with the STEAM conceptual model, authentic tasks are a vital part of what students do during STEAM learning. The goal of these tasks is to mimic what happens in the real world. In this study, we found that teachers who allowed students to direct the learning, offered more inquiry and opportunities for creating authentic tasks. For example, grade four teachers began the unit by allowing students to group based on their interest in a particular topic related to the problem scenario. By doing this, the students began studying different parts of the problem (causes of hearing loss, headphones designs, determining harmful noises, awareness), and the teachers responded by encouraging the students to investigate these problems in ways that made sense to their topic. As a result, the tasks the students were doing (such as measuring typical decibels of sounds heard) were authentic or similar to tasks used when solving the problem in the real world. Additionally, these tasks were aligned to their topic of study and promoted a variety of inquiry paths.

Conversely, if the unit design included many teacher-directed activities such as whole-class discussions or step-by-step instructions for an activity, the implementation was too directed and the teachers noted that students found the work less authentic. Consequently, students followed the steps the teachers presented and did not fully engage in solving the problem through inquiry or use of multiple disciplines. Binkhorst et al. (2017) also noted these inconsistencies between design and implementation, even when teachers were successful in the design stage of the process. Essentially, they described how teachers who believed they had authentically contributed to the process were more likely to implement it to fidelity. In this study, all the teachers designed a unique problem scenario but at times resorted back to previously designed lesson that they felt aligned with the scenario. Because the teachers worked in collaborative teams, it is possible that one teacher felt more ownership over the design process. This points to a need for clarity around the lesson alignment to inquiry and authentic tasks.

Technology and Discipline Integration as Pathways for Authentic Assessments and Student Choice

Throughout the study, we noted if the teachers planned for students to engage with creative technologies and incorporate multiple disciplines, then their ability to assess the students authentically was easier. In authentic assessments, students are asked to apply the knowledge and skills they learned during the STEAM unit in a manner that mirrors what would be done to solve the problem in the real world. Authentic assessment must be aligned with the problem the students are solving, such as using creative technologies in 3D model design or app development. The use of creative technologies promoted discipline integration (involving engineering, science, math, and arts) that mimics what really occurs when trying to solve these types of problems. This success resonates with Kali et al.'s (2015) model for implementing technology beyond instructional technology, that recommends having teachers learn about technology through the design process.

Last, authentic assessments, when designed in a way that aligns with the problem to solve (e.g., using video, podcasting or slides to present a solution or plan, designing and building a model as part of the solution) often taps into students interests through choice because there are multiple ways to solve the problem.

Conclusion

This research demonstrates the importance of teachers designing STEAM curriculum using problem-based units in ways that promote student inquiry. The data demonstrates this is critical to enact discipline integration, teacher facilitation and authentic tasks. However, sometimes there was a mismatch between the designed and enacted curriculum. This mismatch suggests a need to support teachers in specific strategies particular to their curriculum that addresses discipline integration, teacher-facilitation, and authentic tasks. Additionally, while this data only represents one school, there is a clear need for an implementation model specific to grade levels. The supports for kindergarten classrooms and grade five classrooms are vast and varied and should reflect the uniqueness and developmental stages represented in these classrooms. Next steps in this project involve creating systematic support structures that assist teachers during implementation, as well as providing support materials offering teachers guidelines and flexibility in their environment.

Compliance with ethical standards

Ethics Statement All procedures performed in studies involving human participants were in accordance with the ethical standards of the IRB Office of University of Pittsburgh and Clemson University, Reference #19020279.

Informed Consent All participants in the study received the approved IRB forms and were explained the study procedures. Participation in the study was voluntary and the identifiable materials were not published in this study.

Conflict of Interest The authors declare that they have no conflict of interest.

Appendix

Problem-based delivery

This dimension captures the ways in which teacher present material in a problem-based way that is relevant to students' lives

Behavioral indicators	Low (1,2)	Mid (3,4,5)	High (6,7)	Comments
Relevant problems				
Presents students with a problem to solve Explicitly designs tasks which are culturally, geographically, globally, or locally relevant Encourages tasks which are relevant to students' lives	The teacher does not provide problem-based learning	The teacher provides problem-based learning; however the problem is not relevant to students' lives.	The teacher consistently provides problem-based learning that is relevant.	
Connected ideas				
Connections between STEAM content and problem-solving scenarios are explicitly communicated STEAM content is integrated throughout the real-world learning activity.	The teacher approaches problem solving-through inauthentic (unconnected to the problem or not real-world).	The teacher approaches the scenarios by offering students authentic (connected to the problem the students are solving and real world) ideas to consider when problem-solving. At times, content is approaches as an "add on."	The teacher regularly approaches the scenarios by offering students, real-world (content-related) ideas to consider when problem-solving. Content is not approached as an "add-on."	
Acknowledgement of multiple disciplines				
Includes multiple resources Includes methods from different disciplines. Includes multiple concepts from different disciplines	The teacher does not consider knowledge or resources from other disciplines. Resources come from one content area.	The teacher makes some attempt to connect with resources or experts outside of their own discipline, however multiple disciplines are not explicitly considered.	Often, the teacher incorporates multiple disciplines in explicit ways	

Discipline integration

This dimension captures the ways the selection of material across disciplines including concepts, methods and approaches as well as how they are synthesized to support deeper learning

Behavioral indicators	Low (1,2)	Mid (3,4,5)	High (6,7)	Comments
Multiple content areas				
Provides examples in other content areas to make the content meaningful Draws on more than one content area through examples, mentors, resources. References other content areas when teaching another content area.	The teacher focus on a single content area.	Sometimes, the teacher involves more than one discipline to integrate problem-solving through more than one way, however multiple disciplines are not involved.	The teacher consistently involves multiple disciplines through an approach, which integrates context and content. The disciplines are nearly transparent within the problem.	
Multiple methods				
Includes a variety of high quality instructional strategies that encourage/allow students to use	The teacher primarily uses one instructional approach.	Sometimes, the teacher offers one instructional strategy or method is used to meet instructional needs.	Often, the teacher consistently uses a variety of instructional strategies and methods to meet instructional need or various disciplines.	
Synthesis across the disciplines				
Provides curricula, which blends multiple content areas.	No effort is made to integrate content from multiple disciplines.	The teacher offers curricula, which integrates content from multiple disciplines, however curricula clearly delineate the separation of discipline content.	The teacher offers curricula which seamlessly integrates content from multiple disciplines.	

Problem-solving skills

This dimension captures the ways in which teachers foster developing the underlying skills, which are needed for effective problem-solving

Behavioral indicators	Low (1,2)	Mid (3,4,5)	High (6,7)	Comments
Cognitive skills				
Supports honing cognitive skills Abstracting Analyzing Applying Formulating Interpreting Modeling	The teacher does not facilitate building cognitive skills, nor do they provide a platform to apply the skills across settings.	The teacher facilitates cognitive skills but does not consistently provide a platform to apply the skills.	The teacher consistently facilitates skills while providing a platform to apply the skills in a variety of settings.	
Interactional skills				
Student and teacher collaboration opportunities observed Communication (student-to-student or teacher-to-student) encouraged Communication technology employed	The teacher does not provide students with opportunities to collaborate or practice communication skills.	The teachers provide some problem-solving activities in which students can practice communication and collaboration skills. However, the skills are not always practiced relevant to solving the problem.	The teacher provides a variety of relevant problem-solving activities in which students can practice communication and collaboration skills. This may be accomplished in digital and non-digital contexts.	
Creative skills				
Uses multiple tools and methods to allow students creative and varied ways to demonstrate understanding. Behavioral markers might include: student choice multiple approaches encouraged different solutions valued	No effort is made to offer students opportunities to be creative.	The teacher provides instruction uses a variety of tools and methods, however students' choices are limited when constructing creative solutions to problems.	The teacher provides instruction and models a variety of tools and methods for students to consider when creatively constructing solutions.	

Classroom environment

This dimension captures the ways in which teachers structure the classroom environment, tasks, and resources to facilitate deep learning

Behavioral indicators	Low (1,2)	Mid (3,4,5)	High (6,7)	Comments
Problem-based				
Presents students with a problem to solve Presents students with a problem scenario	The teacher does not provide problem-based learning.	The teacher provides problem-based learning; however, the problem does not involve multiple ways to solve the problem.	The teacher consistently provides problem-based learning through ill-structured that encourages students to consider multiple ways to solve the problem.	
Authentic tasks				
Encourages tasks that is relevant to students' lives. Explicitly designs tasks, which are culturally, geographically, globally or locally relevant.	The teacher does not make an effort to make the problem relevant to students' lives.	The construction of the problem includes some tasks connected to student's interests, however the problem is not directly relevant to their lives.	The teachers select tasks connected to students' interest and lives. Tasks within problems are relevant to students' lives.	
Inquiry-rich				
Encourages student-driven approaches to problem-solving. Supports student choice in methods and materials when problem-solving. Allows students to consider multiple questions of study within the overarching problem.	Teachers direct the learning sequentially throughout student's problem-solving.	The teachers construct problems, which offer students guided inquiry in which the question is provided, but student-driven methods or materials are used.	Often, teachers construct problems, which offer student opportunities for open inquiry through students' choice of materials and methods.	
Student choice (method of inquiry, products, group members, process)				
Provide opportunities for student choice in assessment, method of study, partners, etc.	The teacher does not offer students choices in approaching learning content.	The teacher offer students a choice in approaching learning content.	Often, teachers regularly offer students choice in approaching learning content in a variety of ways.	
Technology integration				
Effectively supports learning by engaging students in appropriate technology to problem solve. Technology is used in products, projects or dissemination	The teacher does not choose or integrate appropriate technology for problem-solving.	The teacher chooses appropriate technology; however it is used more as an instructional tool versus a tool to mediate problem-solving.	Often, the teacher chooses appropriate technology and integrate it to mediate problem-solving.	
Teacher facilitated				
Designs tasks to promote student-guided learning. Teachers are assisting with clarifying tasks but not in control of the learning process Students are checking in with one another (collaboration) before seeking help from the teachers. Students are referring to rubrics, problem scenario or other resources when they need assistance.	The problem or tasks are not designed to support student-guided learning.	Sometimes, the teacher designs the problem to support student-guided learning, however the tasks and classroom environment do not always support peer reliance.	Often, the teacher designs the problem, tasks and classroom to support student-guided learning relying on peer support.	

References

Binkhorst, F., Poortman, C. L., & van Joolingen, W. R. (2017). A qualitative analysis of teacher design teams: In-depth insights into their process and links with their outcomes. *Stud Educ Eval, 55*, 135–144. https://doi.org/10.1016/j.stueduc.2017.10.001.

Brush, T., & Saye, J. (2008). The effects of multimedia-supported problem-based inquiry on student engagement, empathy, and assumptions about history. *Interdisciplinary Journal of Problem-Based Learning, 2*(1), 21–56.

Bull, G., Schmidt-Crawford, D. A., McKenna, M. C., & Cohoon, J. (2017). Storymaking: Combining making and storytelling in a school makerspace. *Theory Pract, 56*(4), 271–281. https://doi.org/10.1080/00405841.2017.1348114.

Bush, S. B., & Cook, K. L. (2016). Constructing authentic and meaningful STEAM experiences through university, school, and community partnerships. *Journal of STEM Teacher Education, 51*(1), 57–69. https://doi.org/10.30707/JSTE51.1Bush.

Cohen, J. (2017). Maker principles and technologies in teacher education: A national survey. *J Technol Teach Educ, 25*(1), 5–30.

Cook, K. L., Bush, S. B., & Cox, R. (2015). Engineering encounters: Creating a prosthetic hand. *Sci Child, 53*(4), 80–86. https://doi.org/10.2505/4/sc15_053_04_80.

Cross, N. (2001). Designerly ways of knowing: Design discipline versus design science. *Des Issues, 17*(3), 49–55.

Eisner, E. W. (2002). *The educational imagination*. Upper Saddle River: Prentice Hall.

Fountain, H. (2014). Putting art in STEM. The New York Times. Retrieved from www.nytimes.com/2014/11/02/education/edlife/putting-art-in-stem.html.

Guyotte, K. W., Sochacka, N. W., Costantino, T. E., Kellam, N. N., & Walther, J. (2015). Collaborative creativity in STEAM: Narratives of art education students' experiences in transdisciplinary spaces. *International Journal of Education & the Arts, 16*(15). Retrieved from http://www.ijea.org/v16n15/.

Grimes, S., & Fields, D. (2012). Kids online: A new research agenda for understanding social networking forums. New York. The Joan Ganz Cooney Center at Sesame Workshop. Available online at http://www.joanganzcooneycenter.org/reports-38.html.

Halverson, R. (2005). What can K-12 school leaders learn from video games and gaming? *Innovate: Journal of Online Education, 1*(6), 3.

Henriksen, D., Mishra, P., & Fisser, P. (2016). Infusing creativity and technology in 21st century education: A systemic view for change. *Educational Technology & Society, 19*(3), 27–37.

Hmelo-Silver, C. E. (2004). Problem-based learning: What and how do students learn? *Educ Psychol Rev, 16*(3), 235–266.

Huizinga, T., Handelzalts, A., Nieveen, N., & Voogt, J. (2014). Teacher involvement in curriculum design: Need for support to enhance teachers' design expertise. *Journal of Curriculum Studies, 1*(*46*), 33–57. https://doi.org/10.1080/00220272.2013.834077.

Ito, M., Gutiérrez, K., Livingstone, S., Penuel, B., Rhodes, J., Salen, K., Schor, J., Sefton-Green, J. and Watkins, S.C. (2013) *Connected learning: An agenda for research and design.* Digital Media and Learning Research Hub, Irvine, CA.

Johnson, L., Adams Becker, S., Estrada, V., & Freeman, A. (2014). *NMC Horizon Report: 2014 K-12 Edition*. Austin, Texas: The New Media Consortium.

Kali, Y., McKenney, S., & Sagy, O. (2015). Teachers as designers of technology enhanced learning. *Instr Sci, 43*(2), 173–179. https://doi.org/10.1007/s11251-014-9343-4.

Kaufman, D., Moss, D. M., & Osborn, T. A. (Eds.). (2003). *Beyond the boundaries: A transdisciplinary approach to learning and teaching*. Westport: Greenwood Publishing Group.

Kim, D., & Bolger, M. (2017). Analysis of Korean elementary pre-service teachers' changing attitudes about integrated STEAM pedagogy through developing lesson plans. *Int J Sci Math Educ, 15*(4), 587–605.

Kitagawa, L., Pombo, E., & Davis, T. (2018). Plastic pollution. *Sci Child, 55*(7), 38–45. https://doi.org/10.2505/4/sc18_055_07_38.

Ko, Y., An, J., & Park, N. (2012). Development of computer, math, art convergence education lesson plans based on smart grid technology. In *Computer applications for security, control and system engineering* (pp. 109–114). Springer, Berlin, Heidelberg.

Köppen, E., & Meinel, C. (2015). Empathy via design thinking: Creation of sense and knowledge. In *Design thinking research* (pp. 15–28). Springer, Cham.

Margot, K. C., & Kettler, T. (2019). Teachers' perception of STEM integration and education: A systematic literature review. *International Journal of STEM Education, 6*(2). https://doi.org/10.1186/s40594-018-0151-2.

McFadden, J.R. & Roehrig, G.H. (2017) Exploring teacher design team endeavors while creating an elementary-focused STEM-integrated curriculum. *International Journal of STEM Education*, *(4)*1. https://doi.org/10.1186/s40594-017-0084-1.

Meeth, L. R. (1978). Interdisciplinary studies: A matter of definition. *Change, 10*(7), 10.

Mishra, P., & Kereluik, K. (2011). What 21st century learning? A review and a synthesis. In *Society for Information Technology & Teacher Education International Conference* (pp. 3301-3312). Association for the Advancement of computing in education (AACE).

Nathan, M. J., Phelps, L. A., & Atwood, A. K. (2011). *STEM integration in a precollege course in digital electronics: Analysis of the enacted curriculum*. Proceedings of the American Society of Engineering Education.

National Research Council. (1996). *National science education standards*. Washington, D.C.: National Academies Press.

National Research Council. (2000). *How people learn: Brain, mind, experience, and school*. Washington, D.C.: National Academy Press. Washington, D.C.

NGSS Lead States. (2013). Next generation science standards: for states, by states. Washington, DC: The National Academies Press.

Noguera, P., Darling-Hammond, L., & Friedlaender, D. (2015). Equal opportunity for deeper learning. Deeper learning research series *Jobs for the Future* 1–30.

Penuel, W. R., & Means, B. (2000). Designing a performance assessment to measure students' communication skills in multi-media-supported, project-based learning. In *Annual Meeting of the American Educational Research Association*, New Orleans.

Peppler, K., & Bender, S. (2013). Maker movement spreads innovation one project at a time. *Phi Delta Kappan, 95*(3), 22–27.

Perignat, E., & Katz-Buonincontro, J. (2019). STEAM in practice and research: An integrative literature review. *Think Skills Creat, 31*, 31–43.

Quigley, C. F., & Herro, D. (2016). "Finding the joy in the unknown": Implementation of STEAM teaching practices in middle school science and math classrooms. *Journal of Science Education and Technology, 25*(3), 410–426.

Quigley, C. F., Herro, D., & Jamil, F. M. (2017). Developing a conceptual model of STEAM teaching practices. *School Science and Mathematics, 117*(1-2), 1–12.

Quigley, C. F., & Herro, D. (2019). *An Educator's Guide to STEAM: Engaging Students Using Real-World Problems.* New York, NY: Teachers College Press.

Saldaña, J. (2015). *The coding manual for qualitative researchers*. Thousand Oaks: Sage Publications.

Sanders, M. (2006). A rationale for new approaches to STEM education and STEM education graduate programs. In *93rd Mississippi Valley Technology Teacher Education Conference*, Nashville, TN.

Savery, J. R., & Duffy, T. M. (1995). Problem based learning: An instructional model and its constructivist framework. *Educ Technol, 35*(5), 31–38.

Seymour, G. (2016). The compassionate makerspace. *Teach Libr, 43*(5), 28.

Sheridan, K., Halverson, E. R., Litts, B., Brahms, L., Jacobs-Priebe, L., & Owens, T. (2014). Learning in the making: A comparative case study of three makerspaces. *Harv Educ Rev, 84*(4), 505–531.

Shernoff, D., Sinha, S., Bressler, D., & Ginsburg, L. (2017). Assessing teacher education and professional development needs for the implementation of integrated approaches to STEM education. *International Journal of STEM Education, 4*(13), 13. https://doi.org/10.1186/s40594-017-0068-1.

Squire, K. D. (2007). Games, learning, and society: Building a field. *Educ Technol*, 51–55.

Taylor, B. (2016). Evaluating the benefit of the maker movement in K-12 STEM education. *Electronic International Journal of Education, Arts, and Science*, *2*.

Tsurusaki, B. K., Tzou, C., Conner, L. D. C., & Guthrie, M. (2017). 5th-7th grade girls' conceptions of creativity: Implications for STEAM education. *Creative Education, 8*(2), 255–271.

Wynn, T., & Harris, J. (2012). Toward a STEM+ arts curriculum: Creating the teacher team. *Art Education, 65*(5), 42–47.