K-12 STEM Education
Vol. 4 No. 2, Apr-Jun 2018, pp.331-339

Frameworks to Develop Integrated STEM Curricula

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Abstract

Research-based frameworks can help K-12 schools develop integrated STEM curricula. Two frameworks are presented that describe the characteristics of effective integrated STEM lessons and effective engineering education. The second framework is a modification of the first. Modifications were made to align the framework to a school that was new to integrated STEM. The frameworks have promise for K-12 schools who wish to develop and implement an integrated STEM curriculum that may have different levels of experience and different types of support.

Keywords: STEM education, integrated STEM, curriculum development

Introduction

Many K-12 schools are interested in ways to implement integrated science, technology, engineering, and mathematics (STEM) lessons. One of the strongest motivators for teaching integrated STEM lessons is the research that shows the benefits of these learning experiences. Integrated STEM instruction has been shown to provide more relevant learning (Frykholm & Glasson, 2005; Furner & Kumar, 2007), improved attitudes towards STEM (Hayden, Ouyang, Scinski, Olszewski, & Bielefeldt, 2011), and increased mathematics and science achievement (Hurley, 2001). This paper shares the background and use of two frameworks for integrated STEM curriculum and instruction. The second tool was modified from the original tool to help a school with less experience in integrated STEM instruction.

The Engineering Design-Based STEM Integration Curriculum Assessment

The "Engineering Design-Based STEM Integration Curriculum Assessment" (Engineering STEM ICA) was designed to evaluate the quality of integrated STEM curriculum (Guzey & Moore, 2017). The development of the Engineering STEM ICA included the integration of eight essential tenets of quality STEM integration environments and nine indicators from the framework for quality K-12 engineering education. The eight essential tenets of quality STEM integration environments were identified from a review of research. The tenets include having students: (1) engage with a personally meaningful and motivating context; (2) participate in an engineering design task with a compelling purpose that involves problem-solving skills and ties to context; (3) learn from failure and have the opportunity to redesign; (4) learn appropriate standards-based mathematics and/or science content; (5) explore content with student-centered, research-based pedagogies; (6) participate in teamwork and communication skills; (7) use evidence-based reasoning to integrate engineering with mathematics and/or science; and (8) engage in engineering design throughout the unit (Mathis, Siverling, Moore, Douglas, & Guzey, in press; Moore, Stohlmann et al., 2014). In addition, Moore, Glancy, et al. (2014) developed nine indicators for quality K-12 engineering education that "summarize a quality engineering education for all students throughout their K-12 education" (p. 4). The indicators include: (1) processes of design

(POD) including (1a) POD problem and background; (1b) POD plan and implement; and (1c) POD test and evaluate; (2) applications of science, engineering and mathematics; (3) engineering thinking; (4) conceptions of engineers and engineering; (5) engineering tools; (6) issues, solutions, and impacts; (7) ethics; (8) teamwork; and (9) communication related to engineering.

The researchers recognized relationships between these tenets and indicators. For example, contexts that are personally meaningful and motivating correspond to the issues and impacts that engineers face in the real world. Using these relationships, the tenets and indicators were combined into nine categories for quality STEM integration curriculum. The categories include: (1) a motivating and engaging context, (2) an engineering design challenge, (3) integration of science content, (4) integration of mathematics content, (5) (student-centered) instructional strategies, (6) teamwork, (7) communication, (8) organization, and (9) performance and formative assessment.

Each category numbered above corresponds to the numbers in Table 1 and includes at least four indicators (see Table 1). For example, the "teamwork" category includes the indicator: The curriculum unit requires students to collaborate with others. An extra category called "tools to enhance learning" is included in the Engineering STEM ICA.

The Engineering STEM ICA has been used as a tool in a variety of ways. As a curriculum assessment tool the Engineering STEM ICA has been used to assess the status of engineering in each state's academic science standards, assess drafts of the Next Generation Science Standards, and evaluate the quality of integrated STEM curriculum (Moore, Glancy, et al., 2014; Moore, Tank, Glancy, Kersten, & Ntow, 2013). The Engineering STEM ICA has also been used as a framework for professional development around STEM integration, as a tool to help teachers reflect on curricular units and the representation of engineering, and for the development of K-12 units of instruction (Guzey, Tank, Wang, Roehrig, & Moore, 2014; Moore, Glancy, et al., 2014).

Table 1.
Engineering STEM ICA categories and indicators.

1. A Motivating and Engaging Context
Does the curriculum unit…
Allow students to make sense of the situation based on extensions of their own personal knowledge and experiences?
Engage and motivate students from different backgrounds?
Provide a context with a compelling purpose (what, why, and for whom)?
Include global, economic, environmental, and/or societal contexts?
Include current events and/or contemporary issues?
Provide opportunities for students to apply engineering processes in partially or completely realistic situations?
2. An Engineering Design Challenge
Does the curriculum unit…
Contain activities that require students to use engineering design processes?
Address design elements of problem, background, plan, implement, test, evaluate (or other similar representation of the processes of design)?
Allow student opportunities to participate in problem scoping? This includes, but is not limited to, identifying the client and end users' needs, criteria, constraints, and areas where more background is needed (e.g., establishing the need for the content).
Contain an engineering challenge that requires students to consider criteria, constraints, safety, reliability, risks, alternatives, trade-offs, and/or ethical considerations?
Allow students opportunities to learn from failure/past experiences?

Allow students to redesign?
Contain an engineering challenge that includes a client?
Encourage students to consider the needs of the client and end user (if different than the client)?
Allow students to participate in an open-ended engineering design challenge in which they design and assess processes or build and evaluate prototypes/models/solutions?
Promote engineering habits of mind (e.g., systems thinking, creativity, perseverance)?
Require students to explore or develop technologies (e.g., bridges, water filters, recycling plant processes) from the field of engineering (e.g., civil engineering, environmental engineering, industrial engineering) discussed in the engineering challenge?
Provide opportunities to learn and implement different techniques, skills, processes, and tools related to engineering learning and/or engineering design process learning?
Promote understanding about what engineering is and what engineers do at work?
3. Integration of Science Content
Does the curriculum unit…
Address academic standards in science at levels that match test specifications and beyond?
Integrate science concepts that are grade level appropriate?
Require students to learn, understand, and use fundamental science concepts and/or big ideas of science necessary to solve the engineering challenge?
Promote coherent conceptual understanding of science?
Provide opportunities to learn and implement different techniques, skills, processes, and tools related to science learning?
4. Integration of Mathematics Content
Does the curriculum unit…
Address academic standards in mathematics at levels that match test specifications and beyond?
Integrate mathematics concepts that are grade level appropriate?
Include questions for students that require the collection and analysis of data (i.e., questions match the data)?
Require students to use the data they collect to justify scientific claims and design decisions?
Require students to participate in authentic measurement tasks that link to the science and/or engineering? This might include, but is not limited to, learning how to use measurement tools, thinking about variability in measurements, thinking about sources of error, considering repeatability, and allowing students to develop their own measures and tests.
Promote coherent understanding of mathematical thinking?
Provide opportunities to learn and implement different techniques, skills, processes, and tools related to mathematics learning?
5. Instructional Strategies
Does the curriculum unit…
Contain lessons and activities that are student-centered, minds-on, and/or minds-on/hands-on?
Contain some activities that require students to collect and analyze information or data before arriving at a solution?
Embed evidence-based reasoning as a strategy to connect engineering, science, and mathematics (e.g., data and data analysis provides the evidence for ideas/solutions)?
Include strategies for orchestrating discussions to encourage evidence-based dialogue between teams?
Include explicit connections to the overall design challenge/context in every lesson so that students understand why each lesson is important?
Involve students in activities that embed STEM ideas to be learned in multiple modes of representation (real-life situations, pictures, verbal symbols, written symbols, manipulatives)

with an emphasis on translations within and between modes?
6. Teamwork
Does the curriculum unit…
Require students to collaborate with others?
Include opportunities for students to demonstrate individual responsibility while working in a team?
Build in instructional strategies that encourage positive team interactions and the five elements of cooperative learning?
Require that each member of the team is needed for completion of the activities/tasks?
7. Communication
Does the curriculum unit…
Require students to communicate science concepts (e.g., oral, written, or using visual aids such as charts or graphs)?
Require students to communicate mathematical thinking (e.g., oral, written, or using visual aids such as charts or graphs)?
Require students to communicate engineering thinking/engineering solutions/products (e.g., oral such as presentations to the client, written such as a memo to the client, technical communication, communication to the user, or with visual aids such as schematics)?
Encourage multiple modes of representation (real life situations, pictures, verbal symbols, written symbols, manipulatives/concrete models) within communication of learning?
Include a requirement for evidence-based reasoning in the ways students communicate?
8. Organization
Does the curriculum unit …
Present clear objectives and learning goals from the multiple disciplines of STEM that are tied meaningfully to state standards and, when possible, go beyond these specifications?
Include activities/lessons that flow in a logical and sequential order so they build on each other?
Include engineering context throughout the unit in a manner that allows students to connect the science, mathematics, and engineering learning to the overall engineering design challenge?
Provide guidance and instructional strategies for teachers who are unfamiliar with the unit?
9. Performance and Formative Assessment
Does the curriculum unit include assessments that…
Are closely aligned with the learning objectives and goals and content from the multiple disciplines of STEM?
Are tied meaningfully to state standards and test specifications and, when possible, go beyond these specifications?
Provide students opportunities to produce evidence of understanding and abilities in different ways through performance tasks?
Provide guidance to the teacher that could be used to improve implementation of the curriculum unit?
Extra: Tools to Enhance Learning
Does the curriculum….
Require students to apply technology tools for research, information analysis, problem solving, communication, collaboration, and/or decision making?
Require students to use content-specific digital and non-digital tools to support learning? Digital tools include software, simulations, probes, graphing calculators, web tools, etc. Non-digital tools include protractors, rulers, thermometers, graduated cylinders, spring scales, calipers, etc.

The Integrated STEM Curriculum Planning and Reflection Rubric

In a project working with a departmental based high school (grades 9 to 12), researchers modified the Engineering STEM ICA to support the school's initial attempts to develop and implement integrated STEM curriculum (Walker, 2017). The modifications were based on the departmental structure of the school and their inexperience with integrated STEM instruction. For example, the project only included teachers from the mathematics department and the science department. The teachers were concerned that the Engineering STEM ICA's emphasis on engineering would not allow them to address standards in their content areas. The researchers removed the "engineering design challenge" category and the descriptors were moved to other categories like "engaging context" and "integration of STEM content." These minor modifications helped the teachers feel more confident about including content from their subject areas. In addition, the project defined an integrated STEM lesson as a lesson with content from at least two STEM areas. For example, a lesson would be a STEM lesson if it had learning objectives for science and engineering; mathematics and technology; or science, mathematics, and engineering. This is consistent with the way that Moore, Stohlmann, et al. (2014) define content integration versus context integration. Context integration uses contexts from other STEM discipline areas to make the content relevant. This project used content integration such that "units or lessons have multiple STEM disciplinary learning objectives" (Moore, Stohlmann, et al., 2014, p. 39). As a result, the categories "integration of science content" and "integration of mathematics content" were merged into one category that was renamed "integration of STEM content."

The resulting framework was titled the "Integrated STEM Curriculum Planning and Reflection Rubric" (Walker, Moore, & Guzey, 2017). The rubric includes eight categories: (1) a motivating and engaging context, (2) integration of STEM content, (3) student-centered instructional strategies, (4) teamwork, (5) communication, (6) formative and summative assessment, (7) organization around learning objectives, and (8) integration of technology to enhance learning (see Table 2).

Each category noted in Table 2 included at least two indicators. For example, the "integration of STEM content" category includes the descriptor: The curriculum unit promotes coherent conceptual understanding of at least two STEM content topics.

The "Integrated STEM Curriculum Planning and Reflection Rubric" was used in four different ways for the project (Walker & Bayley, 2017). First, the rubric was the framework for all teacher learning activities. Teachers participated in activities to help them learn about each of the eight categories and how the indicators would be enacted in a classroom. Second, the rubric was used as a lesson planning tool. Teachers cyclically referred to the rubric to see if the curricular units they were designing aligned to the eight categories. Third, the rubric was used as a reflection tool following instruction. Teachers referred back to the tool to see if the enacted STEM curricular unit addressed the eight categories and if the enacted lesson differed from the intended lesson. Finally, the rubric was used to organize the data collection on alignment of teacher practice to integrated STEM. Professional development and program evaluation staff observed each teacher enacting an integrated STEM lesson during the school year. The rubric was used as the observation tool to see if there was evidence of the descriptors for each of the eight categories.

Table 2.
Integrated STEM Curriculum Planning and Reflection Rubric categories and indicators.

1. A Motivating and Engaging Context
Did the curriculum unit…
Provide a context that was interesting for students?
Provide a context with a compelling purpose (what, why, and for whom)?
Include opportunities for students to apply a design process in partially or completely realistic situations?
Engage and motivate students from different backgrounds?
Engage students in STEM habits of mind (e.g., systems thinking, creativity)?
Provide information about what the STEM disciplines are and what people with STEM careers do at work?
2. Integration of STEM Content
Did the curriculum unit…
Require students to use fundamental STEM concepts and/or big ideas of STEM to solve the engaging problem/challenge?
Promote coherent conceptual understanding of at least two STEM content topics?
Integrate STEM concepts that are grade level appropriate?
3. Instructional Strategies
Did the curriculum unit…
Contain activities that are student-centered, minds-on, and hands-on?
Contain activities that require students to collect and analyze information or data before arriving at a solution?
Involve students in activities that embed STEM content to be learned in multiple modes of representation (real life situations, pictures, verbal symbols, written symbols, manipulatives) with an emphasis on translations within and between modes?
Require students to understand and/or take ownership of the engaging problem or challenge?
4. Teamwork
Did the curriculum unit…
Require students to collaborate with others?
Provide opportunities for students to demonstrate individual responsibility?
5. Communication
Did the curriculum unit…
Require students to communicate STEM concepts with other students, teachers, or clients using appropriate content language (e.g., verbally, in writing, or in visual aids such as charts or graphs)?
Require students to communicate STEM solutions, evidence based claims, or products developed in relationship to the engaging context (e.g., verbally, in writing, or in visual aids such as charts or graphs)?
6. Formative and Summative Assessment
Did the curriculum unit include assessments that…
Are closely aligned with the learning objectives and content?
Allow students to demonstrate their understanding and abilities in different ways?
Provide guidance to the teacher that could be used to improve implementation of the curriculum unit?
7. Organization
Did the curriculum unit …
Present clear objectives and learning goals?
Include activities and lessons that flow in a logical and sequential order so they build on each other?

8. Integration of Educational Technology
Did the curriculum….
Require students to use technology for research?
Require students to use technology for information analysis, problem solving, and/or decision making?
Require students to use technology for communication and/or collaboration?
Require students to use content-specific tools, software, or simulations (e.g., probes, graphing calculators, Web tools etc.) to support learning?

Conclusion

The "Engineering Design-Based STEM Integration Curriculum Assessment" and the "Integrated STEM Curriculum Planning and Reflection Rubric" are presented as two frameworks that can be used to build curriculum and enact integrated STEM instruction. Both have been used for teacher learning about integrated STEM and to develop integrated STEM curricular materials. The Engineering STEM ICA has an emphasis on engineering and engineering design which research has shown to be a characteristic of effective K-12 STEM education (Brophy, Klein, Portsmore, & Rogers, 2008). The "Integrated STEM Curriculum Planning and Reflection Rubric" was modified from the Engineering STEM ICA to help a departmentalized school get started on integrated STEM curriculum development and use. The frameworks have promise for K-12 schools who wish to implement integrated STEM curriculum that may have different models (e.g., departmental or team) and different types of support (e.g., common planning time or co-teaching).

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