TẠP CHÍ KHOA HỌC
TRƯỜNG ĐẠI HỌC SƯ PHẠM TP HỒ CHÍ MINH
Tập 16, Số 12 (2019): 918-928

HO CHI MINH CITY UNIVERSITY OF EDUCATION
JOURNAL OF SCIENCE
Vol. 16, No. 12 (2019): 918-928

ISSN: 1859-3100

Website: http://journal.hcmue.edu.vn

Research Article

DESIGNING A STEM INTEGRATED INSTRUCTION FRAMEWORK

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Received: October 08, 2019; Revised: December 13, 2019; Accepted: December 16, 2019

ABSTRACT

STEM education has become a key focus for the upcoming education reform in Vietnam. However, it remains ambiguous for educators to imagine what STEM instruction looks like in the classroom. This article sheds light on the criteria of an effective STEM integrated instruction by analyzing and synthesizing its key characteristics identified by educators from different perspectives. Based on the review of related literature, a STEM Integrated Instruction Framework is suggested in this study as a tool to help teachers to evaluate their STEM lessons.

Keywords: STEM education; STEM integrated instruction; STEM Framework

1. STEM education

1.1. Definitions and characteristics of STEM education

The acronym STEM has its origin in the early 1990's at National Science Foundation (NSF[1]), the United States, referring to the fields of science, technology, engineering, and mathematics. At first, the U.S. government considered it as a solution to the shortage of STEM-related workforce which threatened the country's competitiveness. It then became a widespread movement across many countries. STEM was used as a generic label for any event, policy, program, or practice that involves one or several of the STEM disciplines. Later on, educators began to recognize the efficacy of STEM education to develop students' competencies in order to meet the requirements for the 21st century workforce and started to discuss an integrated approach to STEM education (Honey et al., 2014). A common definition is:

> STEM education is an interdisciplinary approach to learning where rigorous academic concepts are coupled with real-world lessons as students apply science, technology, engineering, and mathematics in contexts that make connections between school, community, work, and the global enterprise enabling the development of STEM literacy and with it the ability to compete in the new economy.
>
> (Tsupros, Kohler, & Hallinen, 2009)

Cite this article as: Bui Thi Thanh Mai (2019). Designing a STEM integrated instruction framework. *Ho Chi Minh City University of Education Journal of Science, 16*(12), 918-928.

[1] NSF is a United States government agency that supports fundamental research and education in all the non-medical fields of science and engineering.

Nguyen (2019), pointed out three characteristics of STEM education from Tsupros, Kohler, and Hallinen’s definition, which are:

- **A1**: an interdisciplinary approach;
- **A2**: academic concepts coupled with real-world lessons;
- **A3**: connections between school, community, work, and the global enterprise.

We would like to supplement a fourth characteristic of STEM education from the preceding definition involving its objective aspect, that is:

- **A4**: development of STEM literacy and ability to compete in the new economy.

These four characteristics can also be found in other definitions of STEM education. One example of this is that A1 and A4 are mentioned in Australia’s Education Council:

> STEM education is a term used to refer collectively to the teaching of the disciplines within its umbrella – science, technology, engineering and mathematics – and also to a cross-disciplinary approach to teaching that increases student interest in STEM-related fields and improves students’ problem solving and critical analysis skills.
>
> (Australia Education Council, 2015)

According to this definition, STEM education can be understood in two ways: i) the teaching of the four separate and distinct fields of science, technology, engineering, and mathematics; ii) the integrated approach to teach these learning areas. Therefore, in the following part of this article, we will use the term “STEM integrated education,” “STEM integrated instruction,” or “integrated STEM” to distinguish this alternative approach from the traditional, disconnected STEM education.

Another definition is given by Sandall et al. (2018). Based on a research utilizing semi-structured interviews of thirteen recognized expert STEM educators, the researchers created an operational definition of integrated STEM to help teachers in their practice:

> Integrated STEM education involves the purposeful integration of science, technology, engineering, and mathematics as well as other subject areas through project-based learning experiences that require the application of knowledge to solve authentic, real- world problems in collaborative environments for the benefit of students.
>
> (Sandall, Sandall, & Walton, 2018)

We can clearly see A1, A2 in this operational definition. A4 is partly implied through the phrases “in collaborative environments,” “for the benefit of students” as collaboration is also an important skill in the 21st century. Besides, a supplementary characteristic can be A5 which is:

- **A5:** project-based learning

In summary, while definitions for STEM vary, there are three areas of commonality: A1, A2 and A4 characteristics; A3 and A5 are added values but not compulsory to all STEM integrated lessons.

1.2. The four STEM disciplines and their relationship

While the acronym is widely used, meanings of each discipline within STEM are sometimes vague, even to those who employ it. Take *technology* as an example, research has shown that, “Teachers used this term to refer to not only the outcome of an engineering design challenge but also to instructional technology (e.g., graphing apps using iPads) to support student learning" (Ring et al., 2017). In addition, there is a common misconception that technology means computing (Sanders, 2009). Hence, it is essential to elucidate the nature of these four disciplines and their relationship.

In the following part, we briefly describe the basic features of the terms: science, technology, engineering, and mathematics:

- Science means natural science, consisting both a body of knowledge that has been accumulated over time and a process - scientific inquiry - that generates new knowledge.
- Technology comprises the entire system (people, organizations, knowledge, processes, and devices) that goes into creating and operating technological artifacts, as well as the artifacts themselves.
- Engineering is both a body of knowledge about the design and creation of human-made products and a process for solving problems.
- Mathematics is the study of patterns and relationships among quantities, numbers, and space.

(Honey et al., 2014)

The connection between the four disciplines can be represented in Diagram 1.

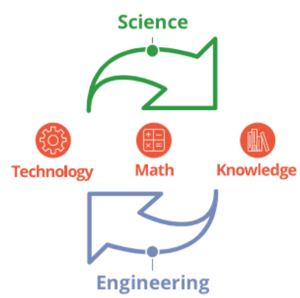

Diagram 1. *Relationship of the four STEM disciplines* (Vigeant, 2017)

- Through the scientific inquiry process and experimentation, new knowledge is gained.
- Knowledge from science informs the engineering design process, enabling us to develop new technology to solve problem. This makes the study of science more effective.
- New technology, in turn, enables further scientific exploration, creating a cycle.
- Both scientific inquiry and engineering design process are facilitated by technology; while math is used to analyze, reason, and communicate ideas effectively, as well as model, formulate, solve, and interpret questions and solutions in science, technology, and engineering.

Thus, the four disciplines of STEM establish a strong connection; mastering it and making it clear to teachers and students is the first step to implement STEM integration into classroom.

2. The need for clarification of effective STEM instruction

While there is a widespread agreement about the importance of STEM, it remains an ambiguous term, particularly in education (Srikoom et al., 2018). There are still a number of misconceptions about integrated STEM education, among which the most common are:

- STEM integrated education is all about programming and robotics.

- Students may lose educational background of humanities and social sciences as STEM integrated education focuses on science, technology, engineering, and mathematics.
- STEM integrated education is expensive due to the high price of equipment.
- STEM integrated education is only suitable for secondary and high school students because it requires complicated skills of engineering.
- STEM integrated education is not suitable for female students.
- STEM integrated education will completely substitute current education programs.
- Teaching four disciplines of STEM distinctly is also STEM integrated education.

(Nguyen, 2019)

Moreover, researches indicated that teachers hold various perceptions of STEM integration (Bybee, 2013). Many teachers report that they feel underprepared to use STEM applications with their students in the classroom (El-Deghaidy & Mansour, 2015). In Vietnam, Nguyen et al. (2018) showed that pre-service teachers' conception of STEM education is quite dispersive. The authors also suggested that it is essential to train teachers more about STEM education so that they can effectively implement integrated STEM in the future. Therefore, we are convinced that the criteria of an effective STEM integrated instruction should be clarified so that teachers have a framework to build their STEM lessons.

3. Criteria of effective STEM integrated instruction

Effective STEM integrated instruction, at first, must reflect the nature of STEM integrated education. This means it must at least satisfy the characteristics A1, A2, and A4. A review of related literature reveals other salient features of integrated STEM teaching. We focus on three documents adopting three different approaches to the subject.

- *Dimensions of Effective STEM Integrated Teaching Practice*: The study explored critical aspects of efficient STEM instruction through observing teaching practice of Thai teachers in 2018. This approach gives us empirical evidence from the context of real classrooms.
- *Framework for STEM Integration in the Classroom*: The framework was developed by Moore and colleagues in 2015, proposing six key elements of integrated STEM teaching. It is the product of recommendations from STEM leaders and STEM educators, guiding STEM curriculum development efforts.
- *A Criteria for Quality STEM/STEAM in San Diego (SDQC)*: Developed in 2014 by STEM Quality Criteria Taskforce – a diverse group of San Diego County teachers of all grade spans, school principals, district administrators, parent-teacher association (PTA)[2],

[2] PTA is an abbreviation for "parent-teacher association". In the U.S, a PTA is a school association run by some of the parents and teachers to discuss matters that affect the children and to organize events to raise money.

university educators, engineers, informal educators, and parents; this tool identifies key attributes of quality STEM/ STEAM programs.

Examining these documents provides us varied perspectives into the STEM criteria from different stakeholders of various education systems.

3.1. Dimensions of Effective STEM Integrated Teaching Practice

Wachira, Chatree, and Deborah (2018) analyzed teaching practice of six teachers to extract common patterns of action in STEM classroom and organized them into four dimensions:

- **D1**: Teacher's role and instruction;
- **D2**: STEM learning context;
- **D3**: Student engagement in design process;
- **D4**: Connecting to content.

Of the four dimensions, D2 is similar to characteristic A2, they all require a meaningful, motivating, linked to real world and STEM careers context. Dimension D4 is explained as an integration of key concepts in STEM disciplines learning through engagement in engineering design. Thus, it reflects characteristic A1 in STEM education's definition as discussed in previous section. The other dimensions belong to instructional strategies and teaching method. D1 suggests that STEM classroom should be student-centered, in which teacher's role is to facilitate and to pose challenging, open-ended questions to engage and encourage students. D3 is itself the Engineering Design Process, which consists of the basic steps shown in Diagram 2.

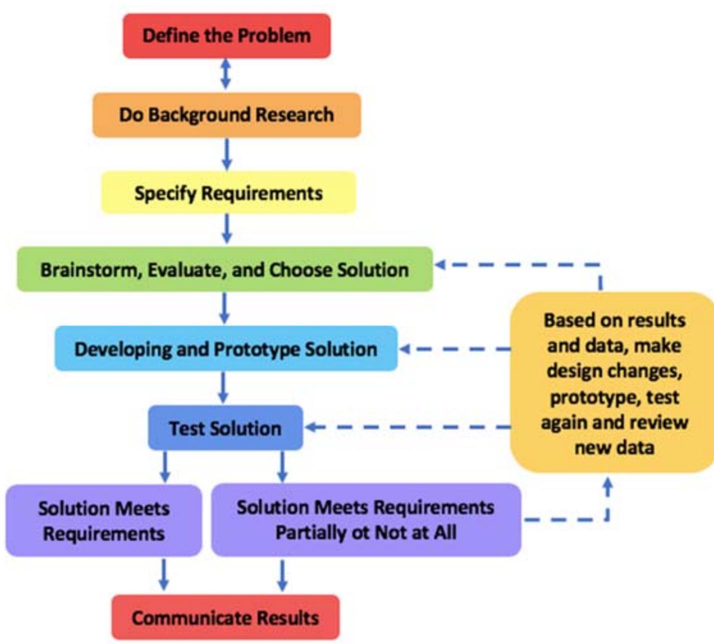

Diagram 2. *Engineering Design Process (Source: Science Buddies)*

It is important that this process is iterative, allows failure and refining ideas, and requires teamwork and communication. These characteristics contribute to integrate engineering and other STEM disciplines as well as to develop 21st century skills.

3.2. Framework for STEM Integration in the Classroom

In the book "The STEM Road Map", Moore et al. (2015) proposed six primary elements of a STEM integrated instruction:

- **R1**: Motivating and engaging context.

The integrated STEM should engage students with meaningful context which allows them to connect to the content. This element is connected to A2 and D2.

- **R2**: Engineering design challenges.
- **R3**: Learning from failure.

R2 and R3 are parts of Engineering Design Process in Dimension D3.

- **R4**: Standard-based math and/or science learning objectives.

This element serves the development of STEM literacy – a component of A4. However, a new requirement is noticed: STEM instruction should include standards-based objectives in order for the learning to be meaningful and worth the time it takes to participate in project and problem-based learning challenges.

- **R5:** Student-centered instruction.

R5 perfectly coincides with dimension D1.

- **R6:** Focus on teamwork and communication.

R6 is a property of D3 and helps to reach the goal of A4.

3.3. Criteria for Quality STEM/STEAM in San Diego (SDQC)

This framework is a tool for schools and program partners to assess their STEM/ STEAM programs. For this reason, SDQC consists of a wide range of elements involving the success of a STEM/ STEAM program. They are divided into four basic attributes:

- Integrity of academic content;
- STEM/ STEAM climate and culture;
- Collaboration among school, community, and industry;
- Connections with college and career readiness.

In this article, we just focus on the elements that directly affect the effectiveness of STEM instruction. Other elements, for instance, on-going professional development in STEM/ STEAM, are conditions to establish a quality STEM/STEAM school or program, which is not a scope of this research. From this point of view, we analyzed and synthesized six criteria for STEM integrated teaching:

- **S1**: Interdisciplinary learning;
- **S2**: Authentic problem solving;
- **S3**: Performance-based tasks and assessments;

- **S4**: Alignment with Standards[3]: instruction focuses on practice, students' discourse, communication, and collaboration;
- **S5**: Collaboration among school, community, and industry;
- **S6**[4]: Essential conditions for STEM/STEAM: Materials and facilities, Equitable access to technology, Dedicated time, and Financial resources.

There are two new criteria compared to six characteristics (A1 to A6) and four dimensions (D1 to D4) that we have already figured out: S3 and S6. They are concerned with assessment and other essential conditions of STEM integrated instruction, such as time, finance, and facilities.

3.4. STEM Integrated Instruction Framework

We analyzed and systematically organized the factors considered into Table 1 according to different instructional components: Learning objectives, Content, Instructional strategies and teaching methods, Assessment, and Essential conditions.

Table 1. *Comparing key elements of STEM integrated instruction*

	Definitions	Dimensions	Road Map	SDQC	Description
Learning objectives	A4	D3	R4 R6	S4	STEM Literacy 21st century skills
	A3			S5	School & Community
Content	A1	D4		S1	Interdisciplinary
	A2	D2	R1	S2	Real world problems
Instructional strategies & teaching methods		D1	R5		Student-centered
		D3	R2 R3		EDP: iterative, allow failure, teamwork
	A5				Project-based learning
Assessment				S3	Performance-based
Essential conditions				S6	Time, Finance, Facilities…

Based on this comparison, we have developed nine criteria of an effective STEM integrated instruction framework and elaborated it with detailed descriptions. We then divided each criterion into three levels which are then described and scored (Table 2, next page).

- For criteria 1, 3, 5, 6:
  - If the instruction meets the criterion (Teacher's answer is Yes (**Y**)), it is at High level;

[3] Standards refer to the Common Core State Standards for English Language Arts and Mathematics, the Next Generation Science Standards, National Core Arts Standards, International Society for Technology in Education Standards, Students and Career Technical Education Standards. They are standards for educational programs in the U.S.

[4] S6 is sythesized from the elements belonging to different components of SDQC.

- If the instruction partially meets the criterion (Teacher's answer is Somewhat (**S**)), it is at Average level;
- If the instruction does not meet the criterion (Teacher's answer is No (**N**)), it is at Low level.

- For criteria 2, 4, 7, 8, 9: Level depends on the number of elements that instruction fulfills (The number of teacher's checked boxes). For instance, if teacher decides that the STEM instruction just applies science knowledge to solve problem, then there is only one checked box (Science) for Criterion 4, the relevant level is Low.

Table 2. *STEM Integrated Instruction Framework*

		0	1	2
Learning objectives	**Criterion 1.** STEM integrated instruction aligns with standard-based STEM disciplines' learning objectives	**N**	**S**	**Y**
	Criterion 2. STEM integrated instruction develops 21st century skills: ☐ Problem solving/ Critical thinking ☐ Communication ☐ Collaboration ☐ Creativity	**0**	**1-2**	**3-4**
	Criterion 3. STEM integrated instruction fosters collaboration among school, community and industry (This criterion is not compulsory for all STEM instruction)	**N**	**S**	**Y**
Content	**Criterion 4.** STEM integrated instruction integrates key concepts in STEM disciplines: ☐ Science ☐ Engineering ☐ Technology ☐ Mathematics	**0-1**	**2-3**	**4**
	Criterion 5. STEM integrated instruction links to real-world and/or STEM careers context	**N**	**S**	**Y**
Instructional strategies & teaching method	**Criterion 6.** STEM integrated instruction is student-centered	**N**	**S**	**Y**
	Criterion 7. STEM integrated instruction is guided by the engineering design process: ☐ Define problem ☐ Iterative ☐ Do background research ☐ Teamwork ☐ Specify requirements ☐ Hands-ons ☐ Brainstorm, choose solutions ☐ Prototype solution ☐ Test, evaluate, improve solution ☐ Communicate solution	**0-3**	**4-7**	**8-10**

Assessment	**Criterion 8.** STEM integrated instruction engages students in performance-based tasks and assessment: ☐ Performance-based tasks ☐ Peer assessment ☐ Formative assessment ☐ Self-reflection	**0**	**1-2**	**3-4**
Essential conditions	**Criterion 9.** STEM integrated instruction is supported with other essential conditions: ☐ Material, facilities ☐ Time ☐ Technology ☐ Finance	**0**	**1-2**	**3-4**
INTERPRETING THE RESULTS: • 15-18 Points: Exemplary STEM • 11-14 Points: Focused STEM • 7-10 Points: Developing STEM (re-evaluate whether it well integrates and/or links to real-world, need improvement before use) • 6 Points or below: Inadequate STEM (possibly rethink if this STEM instruction should be implemented at all)		**TOTAL ______/18**		

- For each criterion: High level gets 2 points, Average level gets 1 point, and Low level gets no point.
- Interpreting the results:
  - Teacher calculates the total point of their instruction out of 18 possible points;
  - STEM integrated instruction is categorized into four groups: Exemplary STEM (15-18 points), Focused STEM (11-14 points), Developing STEM (7-10 points) and Inadequate STEM (6 points or below);
  - Focused and Exemplary STEM are ready to be implemented in practice. Teachers can improve some criteria to get to a higher level (look for low or average level, unchecked boxes);
  - For Developing STEM, first, teacher needs to make sure that important characteristics of STEM integrated instruction are satisfied. Teacher can check the criteria from top to bottom, follow the order of instructional components in Table 2: Learning objectives → Content → Instructional strategies & teaching methods → Assessment → Essential conditions;
  - If the instruction gets 6 points or below, it has high chance of missing the key elements of an effective STEM integrated lesson such as interdisciplinary learning, authentic problem solving, alignment with standard-based STEM learning objectives. Therefore, teacher should carefully reconsider if this Inadequate STEM instruction should be implemented at all.

In the framework, there are significant criteria reflecting the nature of STEM integrated education such as Criteria 1, 4, 5, 7. Other criteria are not specifically linked to integrated STEM. Criteria 2, 6, 8, for instance, are current educational trends for which any instructional approaches aim. However, these criteria are still included in the framework as a guideline for designing and implementing STEM integrated instruction. Criterion 3, as we noted in the framework, is not compulsory for all STEM integrated instruction. We keep it in the framework so that teachers can set a higher goal for their lessons to connect schools and community. Integrated STEM education often requires numerous materials and resources for students and can be costly and time-consuming. Therefore, other essential conditions such as time, finance, technology, materials, and facilities are situated as the last criterion to remind teachers to carefully consider these constraints before putting a lesson into practice. Project-based learning is excluded from the framework because together with inquiry-based learning, problem-based learning, phenomenon-based learning, it is just an instructional approach which teachers adapt to ensure other criteria.

While designing the STEM Integrated Instruction Framework, we tried to describe it in a manner that would be understandable, usable, and memorable for teachers by using checkbox, dividing each criterion into three levels (instead of four or five) and arranging the criteria according to instructional components to make the Framework familiar with teacher's lesson plans.

4. Conclusion

This research has constructed a framework for effective STEM integrated instruction based on the review of related literature of different approaches. It was designed to be easily understood and applied by teachers. In the contemporary context of STEM integrated education in Vietnam, in which teachers are lacking pedagogical content knowledge for teaching STEM, this framework provides a scaffold. Teachers can use the framework to orientate or assess their lesson plans before putting them into practice. Nonetheless, our research has some limitations. First, although we were very keen on reviewing related literature with varied points of view from different stakeholders of an education system, we were only able to review three frameworks from three countries, which is limited. This may not fully cover all characteristics of STEM integrated education. Second, due to the lack of empirical evidence, we were unable to fully confirm the validity of the suggested framework. This could be a focus of our future research.

❖ ***Conflict of Interest:*** *Author have no conflict of interest to declare.*

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XÂY DỰNG BỘ TIÊU CHÍ
ĐÁNH GIÁ HOẠT ĐỘNG GIÁO DỤC STEM

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Ngày nhận bài: 08-10-2019; ngày nhận bài sửa: 13-12-2019; ngày duyệt đăng: 16-12-2019

TÓM TẮT

Giáo dục STEM là một trong những định hướng quan trọng của Chương trình giáo dục phổ thông mới. Tuy nhiên, giáo viên vẫn còn nhiều băn khoăn, chưa hình dung rõ việc triển khai các hoạt động giáo dục STEM trên thực tế sẽ như thế nào. Bài báo xác định các đặc trưng cơ bản của giáo dục STEM bằng phương pháp phân tích các công trình nghiên cứu với những cách tiếp cận khác nhau về lĩnh vực này. Từ kết quả thu được, chúng tôi xây dựng Bộ tiêu chí đánh giá hoạt động giáo dục STEM – một công cụ hỗ trợ giáo viên trong quá trình thiết kế và triển khai các hoạt động giáo dục STEM.

Từ khóa: giáo dục STEM; hoạt động giáo dục STEM; bộ tiêu chí đánh giá