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Engineering Design-Based Learning in Integrative STEM Education

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ABSTRACT

The issue of integrative STEM education is a global one. Great efforts have been made recently to achieve an inclusion of the four areas – science, technology, engineering and mathematics on equal basis in a functioning whole. Science learning through engineering design is presented in this article as an aspect of theoretical integrative frameworks. An example of methodology of lesson' planning based on some characteristic of the engineering design process is also given.

Keywords: engineering design, science learning, integrative STEM education.

INTRODUCTION

The STEM acronym has become increasingly popular. In the early 1990s, when it was used in education for the first time, the main purpose was to focus on the importance of each of the four areas for the future development of the economy and the preparation of staff according to the requirements of the labor market. At that stage two instructional approaches were implemented to realize this idea: (1) the *silo-approach* to enhanced but isolated study of individual disciplines; and (2) the *embedded approach,* where elements of natural science and mathematics are embedded in technological education [1]. It soon became clear that both approaches have their positive aspects, but they generally do not contribute much to improvement of the quality of STEM education.

A solution to the problem should be sought in linking the four directions (science, technology, engineering and mathematics) and developing strategies to incorporate these links into educational approaches that will maximize the benefits of STEM education. This is how the idea of the integral approach and the integrative STEM education (I-STEM ED) appear as a reflection of the natural processes of science integration and need for better education.

A successful implementation of the integral approach depends on finding the right answers to the following questions: (i) can a conceptual framework of I-STEM ED be developed; (ii) what is the place of each of the four areas in this general

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framework; (iii) how will the individual areas be linked in a functioning whole? Undoubtedly, in recent years, the most difficult to understand was the meaning of „T" and „E" in the acronym, as technology and engineering have always remained behind after mathematics and science [2 - 4]. The serious attitude towards this issue contributed to the development of two I-STEM models of conceptual framework: the model proposed by Todd Kelley and J. Knowles [5] and the PIRPOSAL model of John Wells [6]. In both models, the integration is accomplished through the following four elements based on equal grounds: (1) the engineering design and engineering education models; (2) the scientific inquiry and science education inquiry models; (3) the technological literacy and the technological education models, and (4) the mathematical thinking.

There are significant reasons why engineering design is breaking through I-STEM ED and not accidentally is called "the great integrator" [7]. Moreover, the addition of engineering design to STEM is pointed out to be the central aspect of the *New Generation Science Standards* (NGSS) [8, p.108]. That is why it is important to outline the characteristics of engineering design and find out how it interplays with science, technology and mathematics in an I-STEM classroom.

ENGINEERING AND ENGINEERING DESIGN

Honey et al. (2014) define engineering as: "both body of knowledge - about the design and creation of human-made products - and a process for solving problems. This process is design under constraint. One constraint in engineering design is the laws of nature, or science. Other constraints include time, money, available materials, ergonomics, environmental regulations, manufacturability, and reparability. Engineering utilizes concepts in science and mathematics as well as technological tools…" [8, p.14].

The way engineers work traditionally is characterised by the engineering design and this must be the way engineering enters STEM education. In its essence engineering design is a problem-solving approach which means that engineering design-based learning (DBL) is a kind of problem-based learning (PBL). This enhances education by introducing students to authentic/real-life problems, inqury-based approach and hands-on activities to acquire knowledge and reach a solution to the problem. Secondly, engineering design is a systematic and iterative process because it includes steps like planning, modeling, testing, and improving designs that can be repeated (not always in the same order). Other specific feature of the engineering design is that it is a „design under constraints" like time, cost, specific human needs, materials and other limitations. These constraints may be preliminary established, just like the purpose of the design, but they may also undergo changes because of the non-defined and creative nature of the design. That is because problems in engineering are not so „well-defined" as it often happens in mathematics or in a laboratory experiment but mostly they are „ill-defined", which means they are open-ended, may have more than one solution and, moreover, one has to invent the end-solution by his own, without having strict instuctions in the beginning (see Table 1. Well-defined problems vs ill-defined). This is not exactly the case at school where the goal is to learn science and experimentation through engineering design as a context of integration and there are precisely elaborated lesson plans and design briefs given to students for engineering design-based classes [8, p.59]. At the end of this article an example of a lesson plan is given just to show how to implement step by step engineering design in classroom.

Implementation of engineering design may have very beneficial effect on science learning. Its success depends on the collaborative mode of working in a social context. Students have to cooperate in small groups (as engineers do) continuously sharing knowledge and experience and communicating results with all members of

Table 1. Well-defined vs ill-defined problems.

Well-defined problems	Ill-defined problems
Formulaic, procedural	Authentic, real-world, complex
Initial state and constraints – clearly specified	Initial state and constraints – incomplete or unclearly specified
Rules and operations – known	Rules and operations – unknown
Goal – known	Goal - incomplete or unclearly specified
Predicted outcome	Unpredicted outcome; may have more than one outcome
Solution – right or wrong	Solution – neither right nor wrong, but better or worse
Connected to one discipline in general	Higly interdisciplinary
Procedural/ algorithmic thinking, linear	Multiple and creative thinking, non-linear
Addressed to traditional knowledge which is already acquired	Addressed to knowledge which must be inquired
Examples: - prove a theorem; - measure the free-fall acceleration of Earth; - calculate the distance given time and speed.	Examples: - construct a DIY meteo station; - demonstrate energy transformation; - make a proposal how your school can be more energy efficient.

the team and others. The iterative nature of the design process contributes to students' thinking skills development due to constant change between divergent and convergent style of thinking [6]. Nowadays, science and engineering are closely interrelated in way that scientific knowledge informs the engineering design and vice versa new scientific knowledge is not achievable without technological means designed by engineers. Engineering design offers also the unprecedented chance to learn by errors because a prototype of a design is seldom the best choice for the solution, so that the end result is often a product of redesigning.

SCIENCE LEARNING THROUGH ENGINEERING DESIGN

The scientific inquiry is a linear process following several steps when investigating the cause-and-effect relationships of a natural phenomenon: (1) a question about this natural phenomenon; (2) hypothesis; (3) experimental plan; (4) predicted result of experiment; (5) experiment; (6) comparison of predicted and active results; (7) conclusions; (8) if a hypothesis is incorrect than back to (5), else - end [6, p.13].

On the other hand, engineering design is often presented as a circular process with the following 8 stages (with some distinctions with different authors): (1) identify the need or problem; (2) research the need or problem; (3) develop possible solution(s); (4) select the best solution(s); (5) construct a prototype; (6) test and evaluate the solution(s); (7) communicate the solution(s); (8) redesign [6,10]. When integrated in classroom activities scientific inquiry and engineering design are interwoven according to the lesson purpose and core content standards [8].

NRC *Framework for K-12* (2012) identifies as essential for all students to learn and describes in detail the following eight practices of science and engineering:

1. Asking questions (for science) and defining problems (for engineering)
2. Developing and using models
3. Planning and carrying out investigations
4. Analyzing and interpreting data
5. Using mathematics and computational thinking.

Table 2. Engineering design-based lesson format.

Lesson plan **DIY Meteo station**
Grade 10-12
Lesson objectives: *Students will be able to:* - connect sensors to Arduino microcontoller and program them; - construct a weather station under constraints; - send data via wi-fi to a PC, save and interprete data; - make decisions; - chose best solution(s) and communicate it; - work in cooperation and collaboration, etc.
Science education standards: learn physics content in engineering context, make transdisciplinary connections
Crosscutting concepts: measurement, measurement error
Other concepts and vocabulary: temperature, humidity, rainfall, force and direction of wind, sensors, sensor callibration, microcontroller, wi-fi connection
Kits, tools and materials: DHT11 temperature and humidity sensor, BMP180 barometric sensor, LCD and PC, a small prototyping board, wires.
Resources: textbooks, Internet, students' design brief

6. Constructing explanations (for science) and designing solutions (for engineering)

7. Engaging in argument from evidence

8. Obtaining, evaluating, and communicating information [9, p.42].

ENGINEERING DESIGN-BASED LESSON FORMAT

„Developing a truly I-STEM ED lesson requires an intentional and strategic effort when using engineering-design-based-learning to meet necessary outcomes" [7, p.83]. Specific components like purpose/ objectives, core content standards, global or local issue, STEM standards, student outcomes, enduring understandings, driving question and career connection form the basis of the lesson plan [7, p.84]. As science learning through engineering design is connected to the idea of *active learning* and *learning by doing*, where student-centered approaches are leading in the instructional process, then guiding questions addressing specific thinking skills are a key part of the plan. A concise plan structured around these ideas is presented as Tables 2 and 3.

This is a very concise example of a lesson plan but design briefs for students should be more detailed.

CONCLUSIONS

Learning in the context of engineering design helps to understand scientific concepts through their practical applications in an integrated environment. It is necessary for this understanding to enter into formal, informal and non-formal STEM education. The idea of I-STEM ED is not intended to replace the study of individual disciplines, but rather to support and supplement it through all formal and informal means wherever possible.

A good alternative for our country is the use of project forms of school education as well as enhancement of the qualification of teachers through continuing education in world-renowned good practices in the field of I-STEM ED. This is one of many other possible ways to keep our educational system flexible and up to date, on one hand, and raise students' interest in STEM fields and careers, on the other hand.

Table 3. Engineering design-based lesson format.

Engineering design process		
Stage	**Guiding questions**	**Possible answers/ solutions**
Stage #1 Identify the need or problem	Who is the potential client?	Everybody who has a small farm or a garden
	What are we supposed to do? What do we have to design?	A meteo/ weather station based on Arduino
	What is the purpose of design?	To monitor local weather and records parameters such as air temperature, air pressure and humidity in our weather station
	Are there any other goals and objectives?	Does the price allow to connect other sensors to our station, measuring wind speed or rainfall, for example?
	What criteria the design should meet?	The design must be cheap, safe, energy eficient, easy to use.
	Are there any constraints?	The cost must be up to $60 and ready to use in a week
	Can we break the problem into parts?	Yes, we can. (1) Make a research about different sensors; (2) Calculate the price and decide whether to connect other sensors (3) Connect them to an Arduino; (4) Program the sensors; (5) Visualize data on PC monitor or LCD, etc.
	Other questions...	Does the potential client need a wireless connection to the station? Where should be positioned the station? Do we have to rethink over the initial constraints and suggest better solutions under different initial circumstances?
Stage #2 Research the need or problem	What do we know?	Programming an Arduino.
	What else do we need to know?	What are sensors; how to connect and program sensors, how to read data from sensors?
	What questions may we ask? Do we need to contact experts?	Which are the meteorological characteristics of weather? How they influence plants, for example?
	Where do we find additional information?	Internet, experts
	Other questions...	Are there resources or designs from the past we can upgrade?
Stage #3 Develop possible solution(s)	What conceptual knowledge do we need to resort to?	What is temperature, absolute and relative humidity, atmospheric pressure; measurement units; measurement error
	Are all assumptions effective to utilize?	Yes, they are
	Is there something new to bring into the design?	A signaling system for extreme values.
	How to combine different parts of the design?	Team working
	Other questions...	How to protect the station if it is outside?
Stage #4 Select the best	What criteria should the best solution(s) meet?	Accurate readings (sensors calibrated); the station is portable and user-friendly; well-protected from outside influence; safe; energy efficient, etc.
	How to test the chosen solution(s)?	Discover and explore factors that affect measurement errors; find out potential systemstic errors

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