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## Computational Modeling to Enhance Engineering Skills in Prospective Physics and Technology Teachers



**Abstract:** - According to trends in science education research over the past decade, integrated STEM education can not only improve students' conceptual understanding, but also develop various skills in them, such as solving real-world problems by applying theoretical knowledge to everyday life, critical thinking, acquisition of engineering skills, computational thinking, etc. These competences need to be acquired by prospective physics teachers during their preservice studies, as they will be called upon to manage teaching situations on the basis of these competences.

In this paper, we present the experience we have conducted with a group of students, prospective teachers of physics in secondary school, in their fourth year of studies at the École Normale Supérieure de Kouba in Algiers. Throughout the year, students followed a laboratory course in which they learned the fundamentals of computational modeling and applied them to study physical phenomena and systems engineering and determine their behavior in relation to different variables.

We developed a rubric to measure the engineering skills before and after the experience. The findings show an improvement in the mean scores of the students after the experiment which is statistically significant.

**Keywords:** Computational modeling, engineering skills, prospective physics teachers training, STEM education.

### I. INTRODUCTION

The complexity of twenty-first century society demands that education systems prepare individuals to meet the challenges of that society, particularly at the environmental and social levels. This means that individuals must be competitive and ready to apply the knowledge in different disciplines they acquired at school to provide solutions to real life problems they encounter. For this reason, STEM education has been adopted in various countries over the last two decades, and interest in its advancement continues to grow [1].

STEM education is based on the combination of some or all of the four disciplines of Science, Technology, Engineering and Mathematics. The learning objectives are achieved through solving real-life problems which may focus on one of the four subjects, nevertheless the learning contexts must be inspired by the four domains [2].

The authors in [3] attested that to engage students in high quality STEM education, programs must integrate rigorously mathematics, technology and engineering in science curriculum as well as they must promote scientific inquiry and engineering design skills.

Several studies claimed that the teacher's role is one of the crucial keys to successful implementation of integrated STEM education: "Teachers need to have a good understanding of STEM education and need pedagogical training to make learning more meaningful and more interesting for students" [4, p. 2]. However, he should master the basics of technology and engineering design in order to integrate them into science learning. Physics and technology teachers are the first concerned by this, and their preparation is necessary.

Some universities have taken this demand into consideration by developing specific preservice technology teacher preparation program such as Colorado State University (CSU) which integrated an undergraduate engineering degree with teacher licensure for middle school and high school. This approach aimed to develop technology teachers' pedagogical content knowledge related to the infusion of engineering into technology education [5]. In addition, some empirical studies have focused on experimenting programs into physics or technology preservice teachers' curriculum, of different disciplines, with the aim of developing in the latter a content knowledge related to technology and engineering, such as the study in [6] or that in [7], which aimed improving the engineering knowledge and skills of secondary STEM educators to facilitating NGSS adoption in classroom instruction. In [8], the authors claimed the difficulty of assembling technology and engineering in one profession and suggest adding engineering to technology preservice teachers' training. In reference [9], the role of engineering in STEM education curriculum has been emphasised and they pointed out the teachers' ability to teach conceptual and procedural knowledge related to engineering design in order to infuse effectively engineering concepts into curriculum.

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Based on the literature review, we have noticed much fewer empirical studies that focus on how to develop engineering competencies among preservice physics or technology teachers. As a trainer of fourth year prospective secondary physics teachers at the École Normale Supérieure (ENS) of Kouba in Algiers, we give a practical module entitled Computer Science and Experimentation in Physics. The labs in this module aim to develop among the students engineering design skills by using the content they acquire in other courses such as mechanics, mathematics, chemistry, etc. in order to provide solutions to given problems. The main outcomes of these labs are to propose the design of systems, but first, the students must carry out computer-based computational modeling of the physics concepts intervening and/or the suggested solutions. The research questions that guided our study are the following:

- What are the engineering skills that physics' prospective teachers of higher secondary school need to acquire during their preservice training in order to be able to manage STEM learning once inservice?
- Does computational modeling' training develop engineering design' skills in students, physics' prospective teachers of higher secondary school?

In this paper, we present the theoretical framework on which we based to identify the engineering skills in STEM education, the experience we conducted with the students, the data collection instrument and the findings we obtained.

## II. THEORETICAL FRAMEWORK

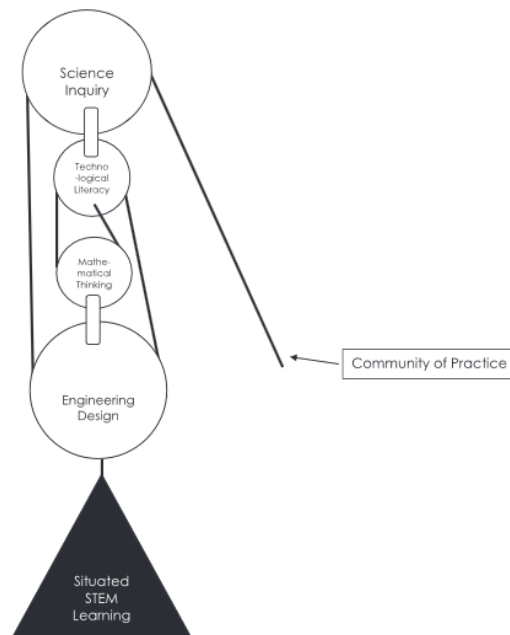
### 2.1 STEM education

The concept of STEM education emerged in the early 1990s [10]. It has been introduced in response to the needs of the 21<sup>st</sup> society for individuals with specific competencies such as critical thinking, creativity and innovation. In addition, the need of a handwork expert in the fields of science and technology, able to meet the current economical, environmental and social challenges [4]. The Washington STEM Study Group created the term "STEM literacy" to describe the ability to identify and apply knowledge from STEM fields to understand and solve challenges that cannot be solved by applying each discipline independently [10].

In STEM education, it is necessary to integrate the four subjects that are science, maths, engineering and technology in a learning session which aims acquiring content knowledge in one of these subjects, theoretical or practical, while emphasizing developing student creativity through real life problem solving [4]. However, there is a broad agreement among educational researchers that the crucial element in STEM education is not only the command of the different STEM disciplines contents but primarily the capacity to recognize and appreciate the connections that exist between these disciplines [2], [3], [4], [9], [10]. Indeed, making connections between cross-disciplinary bodies of knowledge helps students to synthesise knowledge across disciplines and gives the STEM experience an integrative and comprehensive structure that is not limited to a single discipline. [9].

A STEM curriculum design may be focused on: (1) subject-specific content, where it is adopted one or two STEM disciplines as the core theme which is complemented by theme-related knowledge; or (2) integration across several disciplines in a project-based context related to STEM subject knowledge according to the chosen theme [8]. In the first way, the STEM program may focus on scientific and mathematical concepts; engineering design and technology are complementing subjects. Such curricula aim to teach students more complex conceptual knowledge in science. In the second way, the STEM program focuses on engineering design. In reference [8], the authors claimed that centring the learning activities on engineering design represents the best way to implement integrated STEM curricula. According to these authors, an engineering-focused STEM curriculum helps students grasping the engineering discipline and its development, while providing them with experiences in applying cross-disciplinary knowledge and this by using various instructional models such as project-based learning or problem-based-learning [9]. The benefits of engineering-focused STEM curriculum have also been shown in other studies such as [1], [11], [12], [13], [14].

Kelley and Knowles (2016) proposed a graphic model of conceptual framework for STEM learning (Fig.1), where they show the relationships between the four components of the STEM education.



**Fig.1.** Diagram of the STEM learning conceptual framework [1]

The authors advocated that most content in STEM can be grounded within the situated cognition theory which recognizes that the contexts of a learning activity, are critical to the learning process [1]. In a situated learning, the student develops knowledge and skills based on the learning activity; hence in integrated STEM content “engineering design can become the situated context and the platform for STEM learning” [1, p. 4].

### 2.2 Engineering design process in STEM education

As cited above, an engineering-focused STEM curriculum represents a good approach to implement integrated STEM. It involves the use of the engineering design process to integrate various types of knowledge through participation in engineering projects. Engineering design represents the creation of a product or a system as response to a set of human needs, requirements and intentions [15]. It is: “design under constraints and is a problem-solving process satisfying human needs” [9, p. 1525]. The engineering design process requires applying relevant scientific knowledge, mathematical analysis, and technological application. It is: “a form of problem solving, affords students the opportunity to develop 21<sup>st</sup> century cognitive competencies, engages in authentic engineering practices, and integrates science and mathematics concepts” [14, p. 77].

Despite the variety of design processes, the authors in [9] defined six basic steps that are 1) defining the problem; 2) developing solutions; 3) analyzing data; 4) modeling a solution; 5) conducting testing and modification; and 6) optimizing the solution. The first step of the process involves understanding the needs and constraints; it represents the key to clarifying the problem and hence developing solutions, which can be carried out through data collection, analysis, and conceptualization with regards to the defined problem and constraints. It is generally completed by selecting a solution, which must be tested to verify its validity and/or seek its optimization. However, modeling the solution is very useful for testing the solution and its optimization. It represents a crucial step in the engineering design process. It is a representation of the basic features of a product that can take any graphical, physical, or mathematical form on the basis of which the testing, modifying, and optimizing steps are performed [9]. Likewise, it is worthwhile to notice that modeling is not important only in the engineering process for predictive analysis and testing solutions, but also it helps students to improve their conceptual understanding in science and mathematics as well as their performance in engineering design and technology.

Testing, modifying, and optimizing represent also necessary steps in the engineering design process. They involve continuously re-examining problems and refining the details of the design by considering the outcomes of testing and analysis as well as the trade-offs with respect to the different constraints until obtaining the optimal solution [9].

### 2.3 Engineering skills among physics teachers in STEM education

It has been shown in various studies with relation to STEM education that STEM educators lack cohesive understanding of STEM education; they struggle to make connections across the STEM disciplines; they lack

necessary content and pedagogical knowledge to enact cross-disciplinary activities in order to effectively teach integrated STEM contents [1], [5], [15], [16].

As we elucidate above, engineering design skills are crucial in the STEM teachers' preparation, nevertheless, a lack, if not an absence, of these skills has been observed even among technology and physics pre-service teachers programs [5], [8], [15]. The engineering skills that latter may master are given below:

- *Problem identification and definition*: a preservice physics teacher must acquire the competence of identifying problems from the real world; the solution can be addressed through scientific principles, physics concepts, and technology's applications and can be realized through an engineering design. Once in the classroom, he will be able to guide his students to identify real-world problems related to physics, technology, and engineering fields, such as optimizing renewable energy systems, improving transport systems' environmental impact, etc.
- *Research and Investigation*: preservice teachers must acquire the skills necessary to carry out a scientific investigation and learn to integrate it into the classroom by supporting students and helping them to correctly apply the scientific method in information research and by using the concepts and principles of physics and their technological applications, as well as the necessary mathematical tools.
- *Proposing solutions*: preservice teachers should learn how to guide students to propose multiple solutions and prepare the environment where the latter could explore these solutions.
- *Modeling and prototyping*: preservice teachers must master the key competences of creating physical or computer-based models and taking into consideration the different variables that can intervene and the constraints related. Once in the classroom, he will be able to guide his students to develop the necessary models.
- *Testing, analyzing and optimizing*: preservice teachers need to acquire analytical and critical thinking skills so that, once in the classroom, they can guide their students to develop these skills by analyzing their designs using physical principles and technology and encouraging them to optimize their solutions based on evidence.

#### 2.4 Computational modeling in Physics based-STEM programs

In [16], [17], [18], modeling is crucial in STEM education as it takes place in the cognitive dimension of the interaction between theory, experience, and computation. This is even more necessary in the physical sciences, where a large part of the concepts are represented by mathematical models, and grasping these concepts requires the ability to understand these models, to manipulate and develop them, to analyze, to control the variables in the model, and to test them. All these tasks require cognitive activity that uses the results of both theory and experience. The author in [18] advocates the inclusion of computational modeling in an engineering-based STEM program that focuses on physics because the development of knowledge related to the subject depends on it increasingly. When carrying out a modeling process, the student utilizes and develops his knowledge in mathematics and in numerical analysis, as well as his scientific content knowledge. Furthermore, he develops computation thinking [19], scientific and engineering design skills because, during the process, he researches, conceptualizes, suggests models, conducts tests, controls variables, experiences, analyzes, reifies, and optimizes. In addition, programs that integrate computational modeling with the STEM subjects make learning in phase not only with modern scientific research, where computation is as important as theory and experiment, but also with the rapid contemporary development of technology [16].

### III. METHOD

#### 3.1 Laboratory sessions description

Fourth-year physics students at the High School of Teachers ENS of Kouba in Algiers follow a laboratory module named 'Computing and Physics Experiments' which is a three-hour per week annual module. Its general objective is to introduce students, prospective high school physics teachers, to computational modeling and the basis of engineering design. Students at this level of study have in-depth knowledge of the physical sciences, algebra, calculus, numerical analysis, and pedagogical content knowledge. However, they are not able to link this knowledge and apply it in real life situations. Each lab in this module aims to study one theme in physics. The main themes proposed are: ADC converter optimization, control lighting, managing the speed of electrical motors, temperature control, and energy solar panel optimization

### 3.2 The experiment

Before starting the experiment, we devoted two three-hour sessions to explain the STEM education concept and how to implement it in class. In addition, we presented a few video that demonstrate STEM classroom scenarios and the engineering design processes. At the end of each session, we opened the debate to the students in order to identify their conceptions about STEM education, the engineering design, and the computational modeling and give them more information about STEM. Once the experiment started and at the beginning of each session, we presented the problem and invited the students, working into small groups of 3 to 4 students. They had access to connected computers, Arduino Uno kits, and the other necessary materials.

The experiment concerned three labs and lasted approximately 14 sessions of 3 hours each per week with an online continuous collaborative work. During the laboratory session, we guided the students by giving them some information or tips or directed them to relevant documentation, but we did not provide solutions. At the same time, we went around the tables to observe the teams' work and collect the data necessary to evaluate the students' engineering skills and their progress. The three labs' themes are presented in the appendix.

### 3.3 The rubric to determine the students' engineering design skills

In order to answer our research question, we used the triangulation of approaches with an experimental group. Indeed, we used the engineering skills rubric, the students' worksheets analyzing, and the retrospective interview. In this paper, we only present the engineering skills rubric and the results we obtained.

The rubric that we designed contains five items. Each representing one of the skills being measured and each rated on a 0–5 scale. We assigned an observation of unsatisfactory to a score between 0 and 1, moderately satisfactory for a score between 1 and 3, and satisfactory for a score between 3 and 5.

Before using the rubric, we checked its external reliability by passing the rubric to two experts in the field. Then, in order to determine its internal reliability, we passed two same-filled rubrics to the experts. The latter had to give scores to each item, and then we calculated the Cohen's Kappa coefficient and the inter-rater agreement. The Cohen's Kappa coefficient was equal to 0.821, and the inter-rater reliability was equal to 88.6%. These values are statistically satisfactory, which means that the reliability of the rubric has been verified (see the rubric in the appendix).

### 3.4 Data collection

Before the two introductory sessions, we organized two sessions where we invited the students to give solutions to a problem that we proposed (see Appendix). The objective of these sessions is to carry out a pretest to measure the students' engineering skills before the experience.

Concerning data collection, we filled in the engineering skills' rubric during each session and for each team by noting observations of each team's work and then assigning appropriate scores. At the end of the experience, we gathered at an overall 36 filled out rubrics for each theme and 36 others for the pretest.

### 3.5 The study population

The study population consists of an experimental group of 76 students, prospective higher secondary school physics' teachers, in their fourth year of study. We formed randomly four main groups of 19 students each, and then we formed 9 small teams of 2 to 3 students each.

## IV. RESULTS AND DISCUSSION

In order to determine the impact of the introductory sessions and the instruction model of the experiment on the students' engineering skills, we performed descriptive statistics of the students' total scores means obtained in the pretest and during the three labs. The results are illustrated in Table 1.

**Table 1:** Total scores' means

Scores	Mean	Standard Deviation
Scrpretest	3.555	2.8
ScrT1	7.778	2.7
ScrT2	13.638	2.3
ScrT3	17.278	1.2

Table 1 shows the means of the total scores obtained for the pretest lab and the three others. We can see that the means' scores before the introductory sessions were very low with a value of 3.555 and a standard deviation

of 2.8, which is relatively low. So, we can consider that the students had no engineering skills at the beginning of the experiment. Concerning the three laboratories, we note from the table that the means' scores have increased to reach a value of 17.278 at the end of the third laboratory. We can also see that the standard deviation has decreased to the value of 1.2, which means that the students' level of mastery of the engineering skills has progressed and is approximately the same.

Although these scores are relatively low compared to the maximum total score to be achieved in the rubric, we believe that the sessions completed by the students, where they had to practice STEM learning based on engineering design and computational modelling, had a positive impact on the students' engineering skills.

In order to check whether this scores' progression is statistically significant, we have performed an Anova one-factor repeated measures test. The results gave p-values equal to 0.000 for all the multivariate tests, which are less than the value of 0.05. Then, we can conclude that the means of the total scores obtained for each lab are different, and this difference is statistically significant.

Indeed, the instructional model of the sessions' lab carried out by the students during the experience is based mainly on understanding the studied problem, determining the physical concepts and principles in relation, creating the mathematical model, and the computational modeling by performing the numerical study of the model's behaviors trough introducing different values of parameters and variables. The introductory lab was difficult for students; it was necessary to give them more orientations as they did not understand what to do. They were disoriented in terms of the teaching approach because they were used to teaching centered approaches where they followed instructions in laboratory worksheet, carried out manipulations and measured to achieve conclusions that they had already seen in lectures. However, as they practiced the engineering design process, in particular mathematical and computational modeling, simulation, and analysis, they acquired engineering thinking. The hints given at the beginning of each lab and the teacher's guidance had an important role in students' learning progress. We give below some examples of the students' productions:

Figure 2 presents a worksheet of a students' team who got the higher total score in this lab with a score of 4 over 5 for modeling and prototyping competence. The students were very interested by the third theme, which concerned optimization of energy production of solar panels, as the teacher guided them to explore the solar radiation maps and using data to plot the energy production variation of a given panel.

Theme 2: Temperature control

$$T_{int} = \frac{U \cdot A \cdot T_{ext} + \dot{m} \cdot C_p T_{sortie} - u(t)}{\dot{m} \cdot C_p + U \cdot A}$$



Fig. 2. Example 1 of one students' team' production

Figure 3 shows an example of a worksheet of the students' team who got the higher total score, which equals 19 with a score of 4/5.

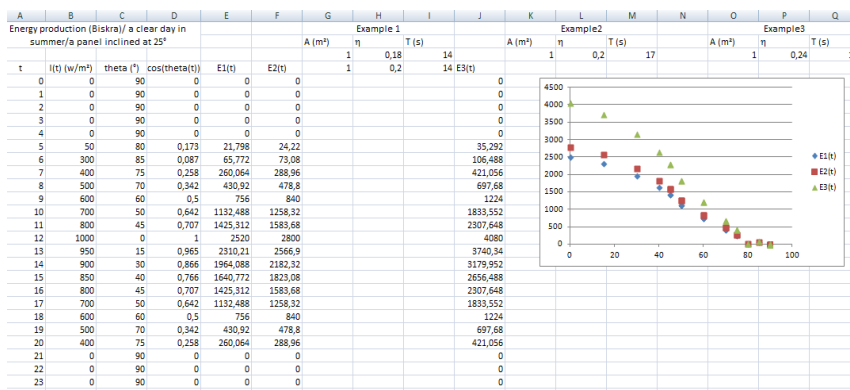


Fig. 3. Example 2 of students' production

## V. CONCLUSION

We have seen in this study that it is important to prepare students, prospective physics teachers, to master STEM skills, notably engineering design skills. We have experimented with a group of students at the ENS of Kouba in Algiers a STEM' learning program based on engineering design, precisely the computational modeling. At the beginning of the experiment, the students had no engineering skills, despite the good scientific and pedagogical knowledge they had acquired during their studies. They were also not used to learning-based STEM approaches. This represented difficulties for them to adapt. However, by increasingly practicing this type of engineering-based learning, we have noted a change in students' practices, which tends towards engineering thinking. Furthermore, the students finished by being convinced that the theoretical concepts and principles, as well as the mathematics they had learned at school or university, could be useful in solving real world problems.

The rubric that we designed allowed us to appreciate the engineering skills' level among the students. The findings showed that there has been progression for all students participating in the experiment, and it is statistically significant.

The limits of the study are the impossibility of achieving finalized solution prototypes and also the impossibility of working on several problems. Regarding the computational modeling, it is preferable to introduce different useful programming languages. Further studies could be focused on these limits.

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**Appendix**

**The Rubric to measure the engineering skills among the students**

Skill	Description	Score	Observations
Problem identification and definition	Indicate if the student has identified the problem, the constraints associated with it and the criteria for success	0 - 5	
Research and Investigation	Indicate if the student has conducted a scientific investigation and collected relevant information related to the subject, scientific content and eventually existent solutions.	0 - 5	
Proposing solutions	Indicate if the student has generated multiple solutions on the base of different hypothesis resulting from the investigation as well as through brainstorming with his peers and creative thinking.	0 - 5	
Modeling and Prototyping	Indicate if the student has developed theoretical, computational model and eventual prototype of the proposed solution.	0 - 5	
Testing, analysing and optimizing	Indicate if the student has carried out tests with different input, data analysis, studied the model/system behaviours, identified strengths and weaknesses, optimized the solution.	0 - 5	

**Table a. Theme 1 - Lighting control**

Problem statement	In a building stairwell, the switches that control the lighting are within everyone's reach. Sometimes by forgetfulness or children, while playing, turn on the lighting during the day which involves wasting energy. In order to avoid this wasting energy, propose a control system that allows switch on lamps from a certain light intensity level.
Physical concepts targeted	The variation of light intensity, the inverse square law, light sensors principles.
STEM competencies	Computational modeling skills, mathematical tools, programming with Arduino, using light sensors, control lighting intensity, optimization.

**Table b. Theme 2- Temperature control**

Problem statement	In a laboratory of vaccine development, the researchers need to stock a chemical molecule at (-25°C) in order to use it in the vaccine composition. You are asked to conceive a system which controls the internal temperature of the refrigerator where the molecule is stocked and maintain it at the desired value.
Physical concepts targeted	Heat transfer and its different modes, thermal energy. Cooling principles
STEM competencies	Temperature sensor use, control and regulating, computational modeling, analyzing and optimizing

**Table c. Theme 3- Optimization of energy production of solar panels**

Problem statement	When installing solar panels, it is necessary to determine the angle of light incidence on the panels in order to obtain optimum energy production. Propose a system which may control the orientation of the panel to produce maximum of energy.
Physical concepts targeted	Solar irradiation, energy conversion, energy efficiency, semi-conductors, incidence angles.
STEM competencies	Design of solar tracking systems, servo-motors, optimization of energy production.