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Teachers realising the role of STEM practices for the development of 21st century skills

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The 21st Century Skills and Competences for New Millennium Learners have been shaping curriculum reforms and educational trends around the world, including in Portugal. In this article we discuss a theoretical perspective on integrated STEM education in which practices have a central place. We consider the current importance of developing professional development programs for teachers, including mathematics, based on a conceptual framework for promoting scientific, technical, and technological knowledge and practices. Our aim is to know how mathematics teachers experience STEM activities and how they evaluate the results of their implementation in the classroom. The study uses a qualitative methodology, in the context of a professional development program. The results show that teachers performed STEM practices in a proposed task and positively evaluated the effects of their students' work on the task, namely in promoting 21st century skills.

Keywords: STEM education, teachers, practices, competences.

Introduction

The 21st Century Skills and Competences for New Millennium Learners in OECD Countries (Ananiadou & Claro, 2009) have had a strong influence in Portugal and were decisive in shaping the overall curricular design of the so-called student's profile at the end of compulsory school (Ministério da Educação, 2017). STEM education is seen as a challenging opportunity to promote the development of such skills and competences. To the public and to most of the educational community, STEM education is seen as something that is new or not yet completely known, especially regarding the ways of putting it into action. On the one hand, STEM education entails connecting science and mathematics knowledge, and their teaching in an integrated way. On the other hand, it includes scientific and engineering practices. Despite the many open questions and unknown terrain, STEM teaching and learning seems to represent a great motivational opportunity to both teachers and students. In particular, the perspective of crafting solutions to real-world problems tends to boost students' interest and curiosity.

There is no more important single factor influencing the quality of a student's educational experience in the classroom than the quality of the teaching and learning practices. Integrated STEM education is particularly relevant to the development of students' skills and competences as it involves solving real-world problems and dealing with complexity.

Teachers make a difference. The success of any plan for improving educational outcomes depends on teachers who carry it out and thus on the abilities of those attracted to the field and their preparation (National Research Council, 2010, p.1).

Professional development programs must offer opportunities for mathematics teachers to engage in meaningful dialogues about integrated STEM education and to develop learning environments for engaging students in STEM activities (Uttendorfer, 2014). Studies have already shown that the STEM initiative is being generally well received by the teachers (e.g., Kang, 2019). In terms of increasing teacher capacity to teach integrated STEM lessons, studies found that teacher professional development courses increased teachers' recognition of the STEM approach and confidence in teaching STEM. Kang (2019) has found that there is a lack of research on the connections between teachers' perceptions of STEM and their classroom practices. In this paper, we focus on mathematics teachers' views and experiences concerning the development of a STEM activity in their mathematics classes, within the context of a professional development program.

Theoretical Framework

Moore et al. (2014) defined integrated STEM education as “an effort to combine some or all of the four disciplines of science, technology, engineering, and mathematics into one class, unit, or lesson that is based on connections between the subjects and real-world problems” (p. 38). We propose a close idea, by assuming integrated STEM education as the approach to teaching the STEM content of two or more STEM domains, bound by STEM practices within an authentic context, for the purpose of connecting these subjects to enhance students' learning.

Kelley and Knowles (2016) advocate that most content in STEM education can be grounded within the situated cognition theory (Lave & Wenger, 1991). Foundational to this theory is the concept that understanding how knowledge and skills can be applied is as important as learning the knowledge and skills itself. Situated cognition theory recognizes that the contexts, which means both the physical and social elements of a learning activity, are critical to the learning process. When a student develops a knowledge and a skill base around an activity, the context of that activity is essential to the learning process (Putnam & Borko, 2000). Often when learning is grounded within a situated context, learning is authentic and relevant, therefore representative of an experience found in actual STEM practices. When considering integrating STEM content, engineering design can become the situated context and the platform for STEM learning.

Engineering design can be an ideal entry point to work in STEM activities or projects. An engineering design approach creates an opportunity to apply science knowledge and inquiry as well as it provides an authentic context for learning mathematical reasoning for informed decisions during the design process (English, 2019). The analytical element of the engineering design process allows students to use mathematics and science inquiry to create and conduct experiments that will inform the learner about the function and performance of potential design solutions before a final prototype is constructed. Both engineering design and scientific inquiry accentuate learning by doing.

Scientific inquiry prepares students to think and act like real scientists, ask questions, hypothesize, and conduct investigations using standard science practices. Engineering and technology are closely related, and if taught in articulation with technology education can promote technological literacy. In fact, engineering and science are closely related to the way in which the technology is used.

STEM education offers students the opportunity to think through technology as a vehicle for change in culture, society, politics, economics, and environment. Studies show that students are more

motivated and perform better on mathematics when teachers use a STEM integrated approach by engaging them in learning activities that include engineering design and prototyping. Incorporating STEM practices that include mathematical analysis necessary for evaluating design solutions provides a powerful basis for students to learn mathematics and to see the connections between what is learned in school and what is required in STEM careers. In this way, students develop their mathematical thinking (Kelley & Knowles, 2016).

According to Kelley and Knowles (2016), the efforts to integrate mathematics and science should be founded, in part, on the idea that knowledge is organized around big ideas, concepts, or themes, and that knowledge is advanced through social discourse. When engaging students into a community of practice, the learning outcomes can be a result of a common and shared practice. A community of practice can provide an opportunity to engage local community experts as STEM partners such as practicing scientists, engineers, and technologists who may help focus the learning.

Leung (2019) argues that teachers need to integrate the correlated STEM disciplines in ways that prevent losing the disciplines' unique characteristics, depth, and rigor. Some STEM models give mathematics and science central roles while others put engineering as the major component of STEM.

Kelley and Knowles (2016) suggest that the key to preparing STEM educators is to first begin by grounding their conceptual understanding of integrated STEM education by sharing key learning theories, pedagogical approaches, and building awareness of research results of current STEM educational initiatives. Furthermore, professional development experiences for in-service teachers may also contribute to a strong conceptual framework of an integrated STEM approach and build their confidence in teaching from an integrated STEM perspective. Kennedy and Odell (2014) claimed that STEM education programs of high quality should include (a) integration of technology and engineering into science and math curriculum at a minimum; (b) promote scientific inquiry and engineering design, include rigorous mathematics and science instruction; (c) develop collaborative approaches to learning, connect students and educators with STEM fields and professionals; (d) provide global and multi perspective viewpoints; (e) incorporate strategies such as project-based learning, provide formal and informal learning experiences; and (f) incorporate appropriate technologies to enhance learning.

Context and method

In the following, we describe and analyse mathematics teachers' experiences concerning the development of a STEM activity in their classes, within the context of a professional development program, and their views about a STEM task. The program was developed over three academic years and involved 243 middle-school (grades 7 to 9) mathematics teachers. All the participants had a professional teaching experience of more than 5 years. The aim of the program was to promote innovative classroom practices and was proposed by the regional educational authorities with the aim of reducing the rate of school failure in mathematics. It was designed according to the recommendations presented in the previous section, namely by integrating STEM practices.

In Figure 1, we present the task proposed: *Customizing paint colour*. The task was solved in small groups, where materials were made available to allow all participants performing experiments related to the re-creation of customized paint colours. The task involves some central ideas/concepts, such

as: colour, mixture, ratio, volume, measurement, formulae, computation, experimentation, technological system, customer, and customizing.

MEMO

From: Sales / Orders

To: Laboratory

Subject: Recreating custom colour

We received an order of custom colour acrylic paint. It is asked to recreate the colour of the curtain sample to paint a wall of a room. The manufacturing section needs to know the composition and quantities of pigments to be used for programming the system to produce various amounts of paint. The quantity of the order is not known (1, 5, 10 liters?).

From the experience ...

You will have to find the colour as close as possible to the sample provided by the customer and obtain its composition. White base and two liquid pigments, measuring syringes and cups to make mixture trials are available. to the model

From the closest possible colour obtained, find out how to manufacture any desired amount of paint, using the white base and the two primary pigments. (Consider the automated paint production system named *tintometric* system, in which a dispensing machine releases exactly the amounts of base and pastes needed to make the client's desired amount of paint).

... and to the final product...

Prepare a report of the work performed, explaining all the processes carried out, the reasoning and the conclusions obtained. You may use the proposed report template.

Figure 1. The task: Customizing paint colour

In Figure 2, we present some of the questions raised to steer discussion and reflection among the teachers, after solving the task. The reflection was intended to include the recommendations by Leung (2019) about how to pedagogically integrate the four STEM disciplines.

1. How does the task involve mathematics and the mathematical modelling process?
2. How do you see the student's learning in carrying out the task? Which ideas, contents, practices, competences are aimed?
3. Which key elements of the Educated Student's Profile do you identify in developing the task?
4. How would you integrate this task in your mathematics classes, namely what would you do before proposing the task and how would you foster subsequent learning after the task is completed?

Figure 2. Questions to guide reflection

The data collection was based on observation and documental analysis. The observation took place in some of the program sessions, in which the teachers solved the STEM task and where discussion periods with the whole group took place. After the program sessions, the teachers were challenged to propose the task to their students, in the class. The teachers were also invited to share their teaching experiences in the following sessions and to present some written reflections. Some excerpts from the teachers' reports shared in a program session will be presented in highlighting some of the results.

Results

The sessions dedicated to STEM education started with an overview and discussion of theoretical and conceptual perspectives and proposals, as suggested by the literature. Although STEM was a novel idea and concept for the participating teachers and they were not used to performing this type of tasks in their classes, the teachers showed a clear enthusiasm and interest in solving such tasks.

While working on the problem of customizing paint colour and performing experimentation with the materials provided (Figure 3), some teachers verbalized their concerns with the implementation of the task in the classroom. They were especially worried about the practical work involving the use of several materials to produce the desired colour.

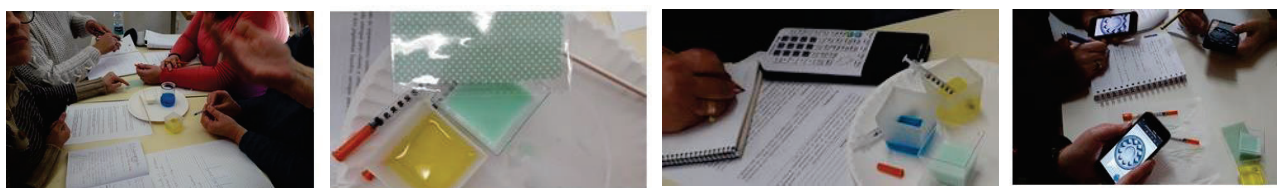


Figure 3. Images of the groups' work using materials and resources

As shown in Figure 3, one consistent finding is that the teachers systematically resorted to the digital technologies they had available. The cell phone calculator and the graphic calculator were always in use in their worktable. Some teachers also used a laptop to do some work with EXCEL. We could observe how the engineering and science practices were closely related to the way in which the technology was used. By challenging the teachers to create a possible simulation of the *tintometric* system, they mainly decided to do it with the spreadsheet (Figure 4).

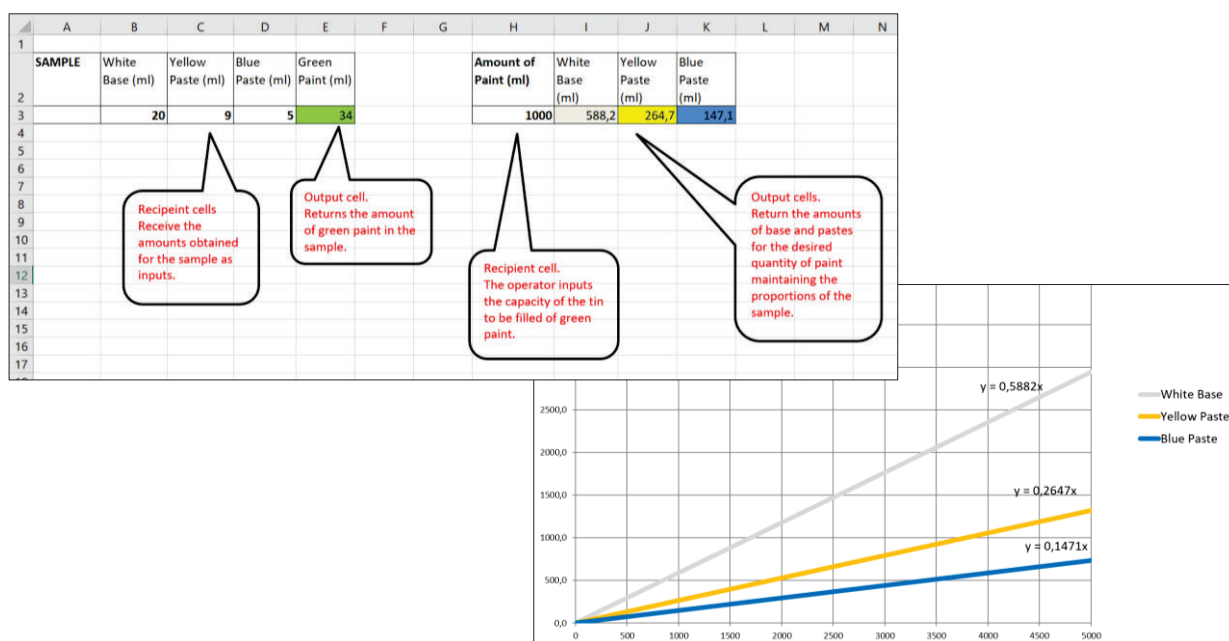


Figure 4. Example of the use of Excel in a mathematical representation of the problem

Effective STEM teachers need more than just expertise in their subject matter, but they also need to be able to use instructional strategies for integrating science, technology, engineering, and

mathematics into their lessons in a way that is both efficient and effective. The teachers showed great enthusiasm and dedication in solving the task, as well as they acknowledged features of the task that they found relevant to an integrated STEM activity. The idea of implementing the task in the classroom was also appealing to most of the participants. Indeed, some time later, several of the teachers used the task in their own classes. Therefore, in a subsequent session, it was possible to organize moments for sharing and discussing the results of that teaching experience.

We selected extracts of two of the teachers' statements regarding their experience with the task proposed to the students in their actual classes.

Teacher 1: Interestingly and to my surprise, the PROFIJ [vocational course] was the class that got the best results in recreating the colour and in the desired accuracy of the amounts of pigments obtained from calculations. I was surprised by the students with more learning difficulties, as they were able to overcome their difficulties with the practical activity of the recreation of the colour.

Teacher 1 proposed the task to students attending a vocational course, where students are aiming to get qualified to perform a job in the workplace. Very often, those students are characterised as highly distracted, usually chatting too much with each other, and often leaving their work unfinished. This is one of the reasons why some teachers refrain from proposing open tasks that require experimentation, collaborative work and using materials. Those students also show little interest on mathematics, have a past of school failure, and may even reject and avoid mathematics. Contrary to what this teacher expected, students' work on the task and the results achieved were unexpectedly positive and the teacher was surprised by the interest, commitment, and enthusiasm of the class in solving the problem.

Teacher 2: The task allowed the development of competencies and skills in **reasoning and problem solving**, as the students had to come up with appropriate strategies to answer the initial questions, generalize conclusions, and create **models to respond to real life situations**. This task has developed **critical thinking and creative thinking**. The students **observed, analysed, and discussed** ideas and processes by **drawing on evidence**. In groups, the students evaluated the impact of the decisions they made. The collaborative work promoted the interpersonal relationship in which the students learned to **consider different perspectives** and to create consensus. The activity carried out allowed for personal development and autonomy. The students **autonomously** designed, implemented, and evaluated strategies to achieve goals and challenges that they set themselves. The skills associated with **scientific, technical, and technological knowledge** were involved when students had to work with **resources and materials, instruments, and tools, relating technical and scientific knowledge** and identifying the technical requirements, the constraints, and resources for the realization of projects.

The comments from the Teacher 2, namely the aspects highlighted in bold, clearly illustrate the recognition of the task's potential to engage students in a STEM project and the teacher's pride on the work developed. Some of the main positive aspects that she and others highlighted after having implemented the task are here summarised: the development of a sense of responsibility, a reinforcement of collaborative work and team spirit, an increase in student's motivation, the development of students' critical thinking, promoting students' persistence in the search for

strategies, and the development of problem-solving skills, mathematical communication, and creativity. Moreover, the teachers considered the work developed on the task as having facilitated and encouraged formative assessment practices aiming at developing students' skills and competences. They asked their students to produce a written report, while encouraging them to search for relevant information on the *tintometric* system. Finally, they were convinced that the work done was important to the students' appreciation of the importance of mathematics in the context of a real professional activity.

The overall results on this activity within the professional development program were quite positive in two aspects. On the one hand, it became evident that teachers formed a positive and attractive idea about the possibility of integrating STEM activities into their teaching practice. On the other hand, when putting the task into practice, many of the teachers were surprised by the way their students got involved, especially the students from vocational courses who are usually little motivated to engage in mathematical activity. In general, to all the participants, the possibilities of the task for the development of 21st century competences and skills have become salient.

Final Remarks

Our study focused on a group of mathematics teachers who attended a professional development program committed to the innovation of teaching practices. Our research methodology assumed a qualitative nature and aimed, above all, to collect evidence about the way they experienced and understood the effect of developing a STEM activity in their mathematics classes.

Regarding their involvement and interaction with the task on the creation of customized colour paint in the course sessions, we have observed that the teachers effectively assumed the scientific, technical, and technological practices involved in the solution to the problem. They have identified and worked on key concepts, namely, mathematical ones, including ratio and proportion. Moreover, they were able to integrate technological resources in their work, including the use of the graphic calculator or the spreadsheet to simulate the various trials they were performing with mixing pigments and the white base, using the materials given. Technical skills involved the need to measure the coloured liquids and to make decisions on the best ways to create the mixture. They have also engaged in discussing ideas about how colour is produced. This indicates that teachers need to be aware of the resources available, both real-world materials and digital tools, to assist them with effective instructional strategies. Using techniques such as project-based and problem-based learning show to be effective methods in STEM approaches.

In what concerns their views on the impact of the STEM activity on the students' learning, we may conclude that the teachers were not only motivated to do practical work in their classes but also to engage their students in solving a real-world problem. Their reflections reveal that after implementing the task the teachers corroborated the positive impact of the activity in their students' development of several skills and competences that are strongly connected with STEM practices. They also reported on the motivational effect observed in lower achievers, namely in mathematics, and on their engagement in finding accurate and sound solutions to the problem.

Our results, although on a limited scale, are relevant and reinforce the conclusions from other studies (Kelley & Knowles, 2016; Kennedy & Odell, 2014; Leung, 2019) in that it is possible to develop

consistent frameworks for integrated STEM teacher education. Emphasising the development of 21st century skills and competences along with STEM practices in addressing the design of solutions to real-world problems appears to be a promising way of promoting integrated STEM education in our schools, at different teaching levels and with diverse students.

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