Teaching Variables and Functions at the Secondary Level in a STEM Context

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ABSTRACT

STEM education is becoming more popular at the primary and secondary levels in many curricula around the world. Effective instructional STEM activities and design methods are required to ensure that students' and teachers' needs are being met. One potential method is the Technology Design Process (TDP): a methodology that stresses the importance of creativity, collaboration and being open to adjustments and compromises. This article reports on a case study that focused on the use of TDP to design and develop teaching-learning materials based on pendulum experiments to introduce variables and functions in mathematical context at the secondary level. The five iterative stages of TDP were integrated into the development of the course materials. Data was collected from 20 high school students who participated in a STEM activity. Both pre- and post-questionnaires were administered to the students. Additionally, a working document was used to assess the students' understanding of abstract concepts and the TDP. The results indicate that TDP-centred activities effectively promote critical thinking, encourage questioning, and facilitate meaningful exploration of abstract concepts.

Keywords: STEM activities, TDP, variables and functions, motivation, pendulum motion.

1. INTRODUCTION

Several researchers have emphasized the effectiveness of inquiry-based thinking activities is enabling students to apply their prior knowledge from different fields to new learning situations that model problem-solving processes. However, it has been observed that many teachers struggle to effectively integrate hands-on activities with engaging cognitive processes during instruction (Nisa, 2021). To bridge this gap and establish meaningful connections between teaching and learning, particularly in the context of technology education (TE), innovative techniques are required to address real-life challenges. Besides, the incorporation of engineering concepts into secondary education, as emphasized by the ITEEA (2007), has broadened the scope of STEM integration beyond just science and mathematics.

Moreover, Dym (1999) highlights that the TE curriculum places a strong emphasis on the TDP, which is an interactive, creative, and practical approach that promotes critical thinking skills. This curriculum encourages integrative learning, which transcends traditional academic boundaries and encourages students to tackle real-world problems and consider diverse perspectives. It is essential to educate students about STEM epistemic practices (Bevan et al., 2019), the principles of technology (Mitcham, 1994) and their integration with other subjects to validate this interdisciplinary approach (Wells, 2019).

In the province of Quebec, the curriculum integrates Science and Technology within the same discipline, while mathematics remains a separate subject. It is important to note that in the Quebec Education Program (2006), the term "Technology" refers to TE. Integrating STEM content within TE is a relatively new practice in the Quebec context. Currently, it is only available in a limited number of schools as elective programs, such as robotics or science and engineering. Moreover, El Fadil et al. (2018) show that the TDP, in Quebec context, is often found to be more technical. Their survey reveals that science and technology teachers have varying understandings of this process, resulting in inconsistencies in its implementation in their classrooms. This confusion could be attributed to factors such as curriculum ambiguity, inadequate teacher training, or a lack of standardized measures for integrated learning.

This proposal aims to introduce seventh-grade students to the concepts of variables and functions through a physics activity centred around TDP. There are two main justifications for focusing on these concepts at this level: historical significance and curricular relevance.

From the historical perspective, the concept of function has long been recognized as crucial in mathematics, with its origins traced back to Galileo's investigations into the motion of a pendulum. Galileo identified variables and explored their quantitative relationship, which led to the emergence of a preliminary definition of a function as an algebraic expression representing the relation between variables (da Ponte & Henriques, 2013).

As part of the curriculum, seventh-grade students have not yet been formally introduced to functions in mathematics or to TDP in technology. This level provides an appropriate opportunity to engage students in STEM activities that incorporate these concepts. By introducing this project, we ensure that students' prior knowledge does not influence the data collected during the study.

1.1. Research questions:

- To what extent do STEM activities enhance students' understanding of both mathematics and TDP?
- How do STEM activities impact students' motivation to grasp abstract concepts and actively engage in technological problem-solving processes?

2. CONCEPTUAL FRAMEWORK

This study draws its foundation from the Haupt (2018) model, which incorporates diverse pedagogical approaches and underlying philosophical conceptions that shape observed teaching practices. The framework considers pedagogy from a practical standpoint, encompassing three modes of transfer: cognitive constructivism, social constructivism, and the technological mode.

Cognitive constructivism focuses on individual performance, emphasizing internal rigor and knowledge construction through the utilization of teaching strategies (Williams, 2016). Social constructivism emphasizes the construction of knowledge through external and social elements, involving interactions with teachers and peers. The technological mode highlights teaching that is facilitated and supported by digital tools and methods.

The philosophical conceptions include four subcategories: epistemology, ontology, methodology, and values (De Vries, 2019; Mitcham, 1995; Svenningsson, 2019). Epistemology relates to the types of knowledge and their sources necessary for designing. Ontology pertains to the nature of mental processes, types of thinking, and psychological characteristics involved in designing activities. Methodology addresses themes centred around the TDP and suggests the structuring of design procedures and strategies. Values encompass soft skills, attitudes, efficacy judgments, ethics, the impact of technology and artifacts, social awareness, cultural, environmental, technical and economic values, as well as environmental sustainability (Haupt, 2018).

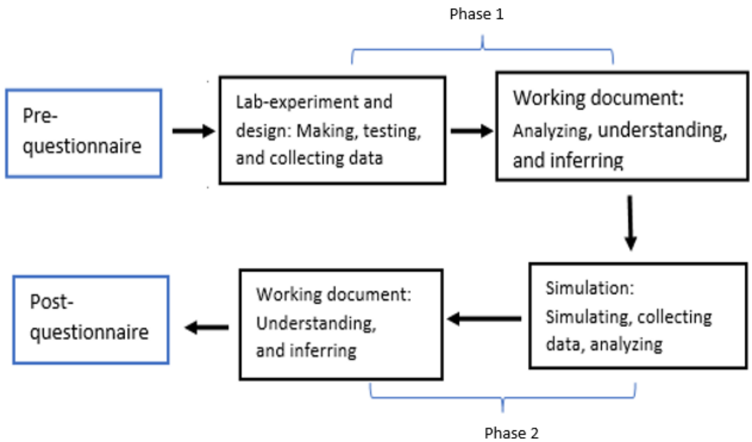
3. METHODOLOGY

To promote transdisciplinary learning through the TDP, our initiative started with a physics activity centered on pendulums. This is justified by the fact that physics not only has natural connections with engineering and technology, but also possesses the capacity to initiate interdisciplinary dialogues and methodologies that transcend traditional disciplinary boundaries (Sinatra et al., 2015).

The project involved designing, making, and analyzing a pendulum, using two teaching phases outlined in Figure 1. The aim was to gain insight into the interrelationships among the variables of the pendulum. Data was collected from a seventh-grade classroom with 20 students. We understand that the number of participants in our study is insufficient to achieve representativeness or support in-depth statistical analysis. This limitation stems from the restricted access to schools due to the ongoing COVID-19 pandemic.

To ensure the credibility of our findings, we followed a case study design and used multiple data sources (Yin, 2003). These sources included pre- and post-questionnaires, hands-on observation during the TDP, as well as a working document that captured students' understanding.

Figure 1.
Project phases of implementation (Source: El Fadil & Najar, 2022)

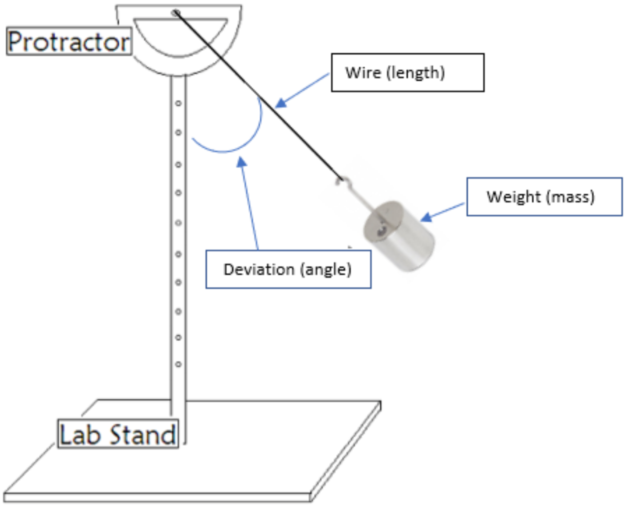


The first phase focused on designing, making and testing of a simple pendulum to explore its function and the variables involved. It began by assessing students' prior knowledge through a pre-questionnaire designed around three fundamental principles: (1) Mitcham's typology of technology, which encompasses objects, activities, knowledge, and volution (Mitcham, 1994); (2) STEM epistemic practices, including investigating, sense-making, and critiquing (Bevan et al., 2019); and (3) content derived from the Mathematics, Science, and Technology subject area in the Quebec Education Program (2006). Students then designed, made, and tested the pendulum using lab-tools to measure its variables. They worked in small teams and generated ideas for designing a simple pendulum, considering the key factors that influence its swings. During a group discussion, students identified mass, length, period, and deviation (angle) as important factors to consider in analyzing the pendulum's behavior. Furthermore, they identified mass, length, and angle as variables that can be controlled (independent variables), while the period of oscillation is identified as the dependent variable, which cannot be controlled.

To explore the relationship between these variables, students were assigned the task of investigating the impact of an independent variable on the period of the pendulum. Collaborating in teams, students engaged in designing, creating, and testing simple pendulums, utilizing a variety of technological tools.

To gather data on the effect of length, students designed pendulums with various lengths of 30 cm, 40 cm, 50 cm, 60 cm, and 70 cm. For each length, they conducted three measurements and calculated the average. Subsequently, they changed the wire (length) and repeated the measurement process. Figure 2 provides further details on this experimental setup.

Figure 2.
An Example of a Simple Pendulum Design



To gather data on the impact of the mass as an independent variable, the group designed a pendulum with a fixed wire and varied the weights suspended to its free end. They used weights of 20 g, 50 g, 100 g, and 200 g. Regarding the angle as a variable, students encountered issues with the stability of the setup, which resulted in the cancellation of its experimentation. After completing the design activities, the students answered questions related to graphical analysis and extrapolation.

In the second phase, students used a simulation tool available on the platform phet.colorado.edu/ to simulate pendulum motions and gather data, replicating the physical experiments conducted in phase 1. The students were prompted to think critically about the accuracy of their results and the ability to draw valid inferences about the relationship between independent and dependent variables. To evaluate the impact of the design activities on the students' understanding of variables, functions and the TDP, a post-questionnaire was administered.

4. RESULTS AND DISCUSSION

The first category of questions in the pre- and post-questionnaires addresses pupils' prior knowledge about pendulums and how they work. Here is a sample of questions provided in the first category:

- Do you know what a pendulum is?
- Can you explain how a pendulum works?

- What type of energy do you think causes pendulums to move?

Data collected from the pre-questionnaire indicates that out of the 20 respondents, only one student did not know what a pendulum is. However, the remaining 19 students confirmed their familiarity with the concept of a pendulum, although many of them struggled to identify its components. Also, only 6 out of 20 respondents were able to accurately identify the parts of a simple pendulum and correctly associate its function with the swinging motion.

Regarding the variables and the type of energy involved in a pendulum motion, only one out of 20 students showed a limited recognition that the mass of the suspended weight and the length of the wire are variables. Similarly, only one student made a connection between energy and the gravitational force.

The second category of questions focuses on scientific and mathematical concepts that are essential to understanding the physics of pendulums. Here are some questions from the second category:

- Explain in your own words what the term "variable quantity" means.
- What method or technique can you use to describe or represent a situation involving two variable quantities?
- Can you determine which variable is considered the independent variable and which one is the dependent variable in a situation where two variables are involved?

In contrast to the first category, the second category of questions display varying levels of understanding. Regarding the meaning of "variable quantity," eight students mentioned that it refers to a quantity that can change. One student stated that it signifies an unknown quantity, another mentioned that it is an expression used in algebra, while the remaining students had no idea about its meaning.

With reference to the method that can be used to represent a situation involving two variables, two students mentioned charts and graphs, while another student mentioned algebraic equations.

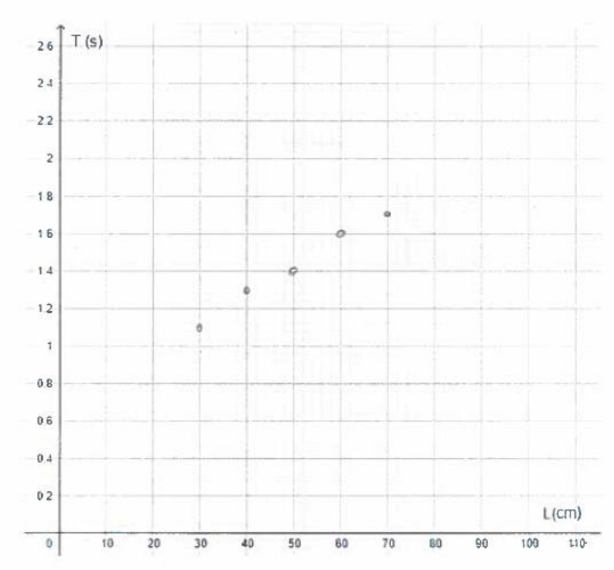
Regarding the ability to distinguish between variables, only 3 students claimed that they can correctly identify which variable is independent and which one is dependent.

The working document provided to the students contains a series of questions that specifically relate to both the process of collecting data from a designed experiment, and how to effectively organize this data into table of values and graphs to make a successful analysis. After designing and making their pendulums, students collected data on length-period variables (excerpt in table 1 and Figure 1). Therefore, they plotted correspondent graphs.

Table 1.
length-period collected data

L: Pendulum length (cm)	30	40	50	60	70
T: Period (s)	1,1	1,3	1,4	1,6	1,7

Figure 3.
Length-Period graph



To gain insight into the students' analysis abilities, we instructed them to use their tables and graphs as references to examine the relationship between the two variables (Length & Period). This task aims to assess not only their proficiency in interpreting and analyzing data based on the visual representations created, but also their ability to think outside the box, by using extrapolation and inference.

The pre- questionnaire's responses indicate that 14 out of 20 students demonstrated the ability to extrapolate their graphs to predict periods for some hypothetical pendulums. For instance, we asked them to determine the periods of the 20-cm-pendulum, 55-cm-pendulum, and 90-cm-pendulum. After analysis, it became evident that the 14 students were able to formulate acceptable answers, as depicted in excerpt 2 (figure 2).

Table 2.
Period Extrapolations and students' answers

Can you determine, from the graph 1, the oscillation period T of	
	Students' answers
a 20-cm pendulum?	T = 1 second
a 55-cm pendulum?	T = 1,5 second
a 90-cm pendulum?	T = 1,9 second

To investigate the relationship between mass and period, students conducted a second experiment. They made another simple pendulum with a fixed length and suspended successively various weights at its free end. The responses indicate a similar level of understanding among the students as in the previous experiment, with the exception that the period varies only slightly as a function of the mass.

The incorporation of digital tools as virtual laboratories has proven to be beneficial for students in enhancing their comprehension of abstract concepts. In the second phase, students replicated the same experiments conducted in phase 1, but in a virtual environment. This activity provided students with an opportunity to reflect on the advantages and limitations of physical laboratory experiments, simulations, as well as modelling. Through this second phase, students learned how the virtual environment empowers them to surpass the limitations imposed by the physical constraints of the lab-equipment. It allowed them to explore and push the boundaries of their knowledge in ways that may not have been possible in the traditional lab setting. The responses indicate that 14 out of 20 students successfully collected data from the simulation platform, generated graphs, extrapolated data, and provided answers to related questions.

After completing the second phase, we administered them the post-questionnaire. The analysis of the post-questionnaire data reveals that all students had acquired a comprehension of the steps involved in the TDP and had a clear understanding of both what a simple pendulum is, and how it works. Additionally, 16 respondents demonstrated an understanding of the connection between the function of a pendulum and the period of its swings, which is influenced mostly by the length of the wire.

However, the analysis of both the post-questionnaire and the working document indicates that only two out of the 20 students were able to make a correlation between the force of gravity and the potential energy involved in the oscillating motion of the pendulum. To gain a deeper understanding of the impact of this project on mathematics learning, we included a question about the inverse function in the working document. We prompted the students how they could make a pendulum that would achieve a specific period of oscillation. For instance, we inquired whether they could calculate the length of pendulums that oscillate respectively with periods of 1.00 s, 1.40 s, and 2.00 s.

The responses indicate that 11 out of 20 students have used their graphs by initiating their lines from the y-axis, which represents the period, to determine the lengths (on the x-axis) of the three hypothetical pendulums, as demonstrated in excerpt 3 (Table 3).

Table 3.
Inverse function questions and students' answers

Can you determine, by using graph 1, the length L of pendulums that have different periods of oscillation?	
	Students' answers
a 1,0-second pendulum?	L = 20 cm
a 1,4-second pendulum?	L = 50 cm
a 2,0-second pendulum?	L = 70 cm

5. CONCLUSION

Integrating technology-driven activities centred around pendulum motion into the TDP framework can significantly enrich students' learning experiences by fostering collaboration and facilitating hands-on exploration. These activities offer students opportunities to design, manipulate, and develop problem-solving skills while gaining a deeper understanding of concepts such as variables and functions.

By engaging in design and hands-on explorations, students have the opportunity to enrich their comprehension not just of the TDP but also of the principles governing simple harmonic motion and variables, particularly focusing on the relationship between the period and the length of the pendulum. Active engagement in TDP-centred activities empowers students to create innovative solutions, analyze data, identify models, and establish connections between variables. This experiential learning approach encourages critical thinking, questioning, reasoning, and meaningful exploration of concepts. Additionally, collaboration among students during these activities provides opportunities for peer learning. Students can share ideas, discuss their observations, and work together to solve problems and explore different approaches. This collaborative learning environment nurtures communication skills, teamwork, and the ability to consider multiple perspectives. Overall, the inclusion of STEM activities in the TDP context empowers students to actively engage in their own learning, develop a deeper understanding of STEM concepts, and build essential skills that can be extended beyond the classroom.

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