Design of STEM Activities: Experiences and Perceptions of Prospective Secondary School Teachers

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Abstract—STEM education is attracting the attention of researchers in the education of science, mathematics, technology and engineering, for it encourages school practices that prepare students for real life professions. An important aspect of STEM education is the design of STEM activities, for this design influences how the activities mediate students' experiences in the STEM classroom. In the present chapter, we suggest to consider this design in two lenses: The lenses of the activity inquiry and the lenses of the integration of STEM subjects. We further describe activities built by secondary school prospective mathematics teachers who were part of a teacher education program for preparing graduate students who finished their first degree in mathematics, engineering or computer science. The prospective teachers designed the STEM activities in the frame of a didactic course called "The didactics of teaching secondary school mathematics". The research results indicated that the prospective teachers found it difficult to write STEM activities according to the 'discovery inquiry version' or the 'open inquiry version'. Moreover, they found it difficult to write activities according to the third or fourth integration types.

Keywords—STEM education, STEM activities, activity design, prospective teachers, secondary school

1 Introduction

STEM education has been the focus of many curriculums in recent years. It emphasizes the integration between four subjects (Science, Technology, Engineering and Mathematics) in order to engage in real life problem solving [1]. The demand for the STEM topic is influenced by the change of real life demands and the change of the universal economy. This change resulted in the need for STEM workers, and this need indicated the need for STEM education, teachers and students [2].

Ref. [2] noted that high quality STEM education programs should include

- Integration of technology and engineering into the curriculum of science and mathematics at the very least
- Promote scientific inquiry and engineering design, including rigorous mathematics and science teaching
- Collaborative approaches to learning, connecting students and educators with STEM and professionals
- Provide a global and multi-perspective
- Integrate strategies such as project-based learning, providing formal and informal learning experiences
- Incorporate appropriate technologies to improve learning

Engagement in STEM activities has different effects among learners:

- Fostering learners' abilities to solve problems ([3], [4]) by fostering knowledge, attitudes, and skills to identify questions and problems in life situations [5]
- Fostering abilities to invention and innovation
- Developing self-reliance
- Developing logical thinking
- Increasing the literacy across the technological and scientific areas [3]
- Motivating students to careers in STEM fields and may improve their interest and performance in mathematics and science [4]

These effects are due to that STEM integration offers students opportunities to experience learning in a real world situation, rather than to learn non connected pieces of knowledge [6] and support student development of 21st century competencies and skills [7]. In addition, it allows teachers to focus on big ideas that are situated or interrelated between subjects. STEM integration is facilitated through the design of STEM activities, which is the focus of the present chapter.

Effective designing of STEM activities is considered an important role in integrated STEM in learning teaching [8]. Several studies suggest different principles in order to achieve this aim. Principles based on motivating students through different processes of engagement in STEM activities were suggested by ref. [9] that described four conditions for designing technology activities to teach mathematics:

- Motivating sustained engagement trough problem design, so design of the activity must promote student engagement at the beginning of a lesson through its end
- Motivate on-target thinking through foregrounding, so students also need to become cognitively engaged with the target math ideas
- Motivating generalization by making the process the product, which enables to think about the mathematics at a deep level to be able to describe the general aspects of situations
- Motivating explanation by incorporating a client that activity provides an authentic reason for students to explain their thinking

Other researchers considered the curriculum component for successfully integrating STEM content through specific activities, and suggested principles to get this aim. Ref. [9] emphasized 6 principles:

- Contextualize all student work within STEM-design challenges
- To define the specific course goals
- The instructional framework based on a standardized engineering design process
- Involving students from the first of the learning process
- All science and math concepts, and technology tools employed are necessary for students' successful completion of the STEM-design projects
- To understand the constraints of high school and school district systems.

1.1 Activity design

The issue of activity design is attracting the attention of educators in the mathematics classroom (e.g., [10]), the science classroom (e.g., [11]) and the STEM classroom (e.g., [12]). Ref. [12] described how they designed and implemented STEM activities: Basing the assignment on problem-based situation with conditions and limitations provided; clearly identifying the objectives of the STEM activity; providing a set of related knowledge and integrating the principles of science, mathematics and technology; etc. We argue that the previous description is of the phases of designing STEM activities. The present research is interested in the aspect of design rather than phases. Below we elaborate these aspects. This is in line with the claim of ref. [13] that engaging teachers in curriculum design is critical for improving integrated STEM education. In addition, the present paper tells the story of secondary school prospective teachers that experienced design and implementation of STEM activities. Doing that, it describes their experiences in terms of the design aspects.

In addition to the above, one aspect that researchers paid attention to when designing STEM activities is the inquiry in these activities.

Inquiry in scientific activities: The National Research Council, in [14], says that inquiry-based learning can range from highly teacher directed to highly student directed. The levels of inquiry, according to this description, are structured inquiry, guided inquiry, open inquiry and coupled inquiry. These levels are described below.

Structured inquiry: In this type of inquiry, the students investigate a question provided by the teacher through procedures and methods that the teacher describes. These procedures or methods contain detailed step-by step instructions for each stage of the investigation. Ref. [15] describes structured inquiry as a linear inquiry process that begins with identifying a related question, through data collection, and ends with the drawing of appropriate evidence-based conclusions. They conclude that structured inquiry fits the situation where results are 'known in advance', so it works well only for developing basic inquiry skills that are inadequate for appreciating the real nature of science.

Guided inquiry: In this type of inquiry, usually the teacher chooses the question for investigation. Ref. [15] says that in guided inquiry the teacher provides the student with inquiry questions and procedures, and therefore this decreases the level of uncertainty during the inquiry process. This enables the students to lead the inquiry process, through decision making from the data collection stage, which results in making conclusions from the inquiry.

Open inquiry: In this student-centered approach, the teacher supports the students to pose, individually or in groups, questions that they try to answer through designing and conducting an investigation and communicating results. Open inquiry requires higher-order thinking and usually has students working directly with the concept and materials, equipment, and so forth [16]. That will lead students to deepen their mathematics learning [17] and demonstrate ownership and responsibility for determining the purpose of the inquiry and the question to be investigated as a scientist would [18].

Some researchers add another level to the above three levels called the confirmation level (e.g., [19], [20]). The four levels become: confirmation, structured, guided, and open. In the confirmation level, a question as well as a procedure needed to answer it are given to the students who follow the procedure to confirm a previously given answer for the problem.

A second aspect that researchers paid attention to when designing STEM activities is the integration of the STEM subjects in these activities.

Type of the integration of the STEM subjects: There are three instructional models employed for implementing integrative curricula, multidisciplinary, interdisciplinary, and transdisciplinary [21]. Regarding the nature of connection in STEM, Ref. [22]) says that STEM education could integrate concepts from the four subjects in STEM. This integration varies, for it could combine two practices or connect a concept from one subject to a practice of another. They further argue that it is frequently the case that one STEM subject has a dominant role, while concepts or practices from other subjects are intended to support the understanding of concepts or practices in the targeted subject. The previous description of the types of integration among the subjects in STEM education leads to four levels of this integration. In the first level, STEM activities involve the combination of just two subjects, where the first subject is dominant, while concepts or practices from the second subject supports the emergence of concepts from the first. The second level is similar to the first, but here three subjects or more are involved in the STEM activities. Thus, in the second level, one subject is dominant, while the other two or three subjects support supports the emergence of concepts from the first. In the third level, just two subjects are involved and concepts from the two emerge as a result of the integration. The fourth level is similar to the third, but here at least three subjects are involved, where concepts from two of them at least emerge together, while the rest of the subjects support these emergences.

According to those who consider mathematics as a language for the other subjects [23], mathematics should be essential in STEM activities and help explain concepts from other subjects [10]. Another suggestion emphasize that mathematics need to be transparent and explicit, because some students will have difficulties in noticing that mathematics is inherent in STEM activities [24]).

1.2 Research rationale and goals

Inquiry in classroom scientific activities and integration of disciplines in this classroom are two important features of learning in this classroom ([25], [26]). In the present research, we suggest to consider the design of STEM activities in the lenses of two frameworks: the inquiry framework and the integration of STEM subjects framework. This design, in light of the two lenses, is the focus of the present chapter. We intend to describe the experiences of prospective mathematics high school teachers in designing STEM activities and their perceptions of these activities as tools with which high school students learn mathematics. Ref. [10] says that "teaching mathematics in a technology classroom requires more than simply using mathematics with technology. It requires designing the lesson to focus, motivate, and highlight the mathematics in a meaningful way" (p. 21). This is also true for the STEM classroom, which also highlights the need for studies that focus on activity design. In the present chapter, we attempt to address this issue.

2 Research Methodology

2.1 Research context and participants

The present study tries to suggest aspects of design of STEM activities, which would benefit educators who come to design such activities. It depended on the literature in order to suggest such aspects. In addition, the present study describes the experiences of prospective secondary school teachers in designing and implementing STEM activities.

Ten prospective secondary school teachers participated in one-year preparation to become secondary mathematics teachers. The prospective teachers were part of a teacher education program for preparing graduate students who finished their first degree in mathematics, engineering or computer science. The prospective teachers worked in four groups to design the STEM activities in the frame of a didactic course called "The didactics of teaching secondary school mathematics". These groups could be described as 'study groups' according to [27].

2.2 STEM activities as part of the prospective teachers' program

One topic that the prospective teachers studied in the didactics course was STEM education. This education was expected to fit the participants because they came from STEM background. The introduction of the STEM activities was done through group work, where the prospective teachers worked in groups of two to three in order to design STEM activities. After the groups' activity, each group presented the activity designed by them, and the whole class discussed the activity and its aspects.

2.3 Data collection tools

The data was collected through a couple of tools. The first tool is the video recording, where the discussion of the prospective teachers in the whole class was video recorded. This discussion involved the design process by the prospective teachers, the aspects of this design and the prospective teachers' opinions regarding the fitness of the designed activities to the secondary school mathematics students. The second tool is the activities designed by the prospective teachers.

2.4 Data analysis tools

To analyze the data, we used inductive and deductive qualitative content analysis. Content analysis is a process designed to condense raw data into categories or themes based on valid inference and interpretation that use inductive reasoning.

We used deductive content analysis [28] to consider the design aspects of the activities. We depended on the literature to do that. Utilizing the literature, we adopted two aspects: Inquiry and integration of subjects. In a later phase, we used deductive content analysis to analyze the participants' designed activities. Doing that, we took into account the four types of inquiry activities (confirmation, structured, guided and open), as well as the four types of integration of the subjects of STEM activities (Combination of two subjects with one dominant subject, combination of at least three subjects with one dominant subject, combination of two dominant subjects, and combination of at least three subjects, where two of them are dominant).

To analyze the participants' discussions, we used the inductive constant comparison method. This enabled to arrive at themes related to the participants' perceptions of STEM activities from the different types according to the aspects.

3 Results

3.1 Model for the design of STEM activities

We suggest, depending on the literature, that the design of STEM activities takes into consideration two aspects: The inquiry level in the activity and the integration type of the activity. As described above, the inquiry level could be: confirmation, structured, guided and open. At the same time, the integration type could be: Combination of two subjects with one dominant subject, combination of at least three subjects with one dominant subject, combination of two dominant subjects, and combination of at least three subjects, where two of them are dominant.

3.2 Prospective teachers' experiences and perceptions of the design of STEM activities

We describe below the prospective teachers' experiences and perceptions regarding designing the STEM activities. To do so, we refer to two features of the activities: the level of inquiry in the designed activities and to the level of integration of the STEM subjects in the activities.

The level of inquiry of the designed activities: According to the inquiry level in designing activities, we identified familiar features among all the groups of prospective secondary school teachers who participated in the research, where these features indicated three levels of inquiry. At the beginning, the entire group start in the confirmation version, and then they develop the activities into the structured version. No group could alone arrive at the open version. Figure 1 present the development of the levels of inquiry among the groups.

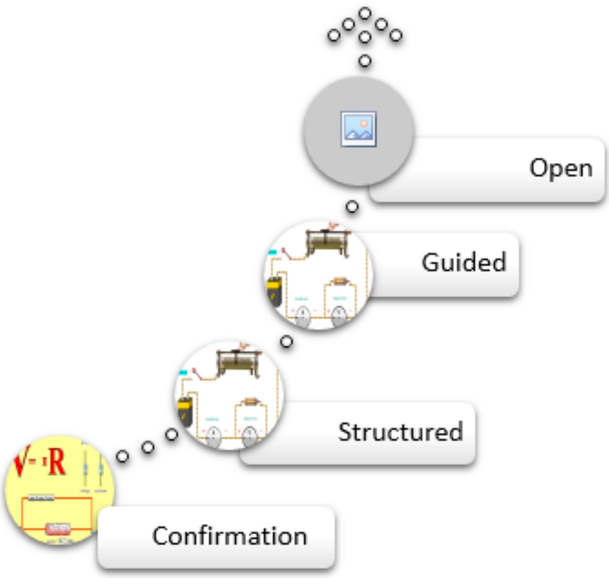


Fig. 1. The development of the inquiry level among the groups

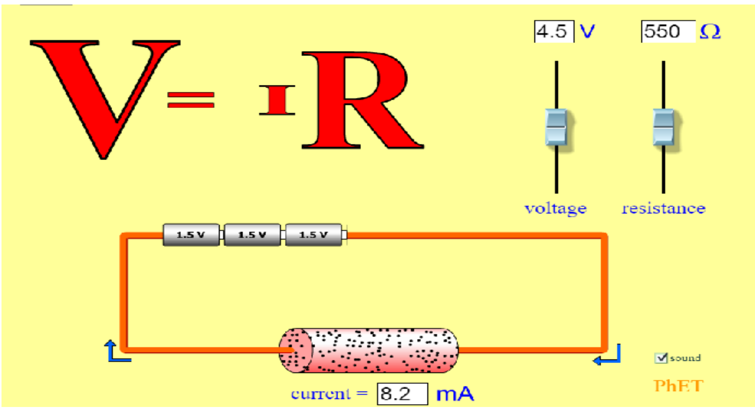
The prospective teachers discussed the four inquiry levels, at the beginning in a group of two or three, and afterwards with the instructor. Inquiry based activities, except the confirmation version, were perceived by the prospective teachers as strange at the beginning for the prospective teachers. They were used to the confirmation version; i.e. to activities that include the rules of the new material, and then requesting the students to confirm these rules. After discussing each level, the prospective teachers were requested to write an activity according to this level. Below, we describe the prospective teachers' work with the activities and some of their sayings regarding them. Due to limitation space we will present the development of one activity only (Ohm's law).

The confirmation version, the case of Ohm's law: The confirmation version was familiar to the prospective teachers, as they were used to activities that satisfy this level and adopted them as means for learning and teaching in the science and mathematics classrooms. This version was considered by the prospective teachers as the common way for teaching and learning, as clarified by one of the prospective teachers who claimed: "This is the way we learned at school and at university. The role of the students is to practice the rules that the teacher passes to him. These rules are given in the textbook and the teacher passes them to the students. The teacher is successful when the students understand these rules by verifying and then practicing them".

The conformation activity that was suggested by one group for the Ohm's law at the beginning of the course was the following:

Ohm's law states that the current through a conductor between two points is directly proportional to the voltage across the two points. The constant proportion of the relationship between the voltage and the current is the resistance. The gives the algebraic equation: V=IR, where I is the current through the conductor in units of amperes, V is the voltage measured across the conductor in units of volts, and R is the resistance of the conductor in units of ohms.

Work with the simulation called Ohm's law at the PHET site[1] to understand this law.

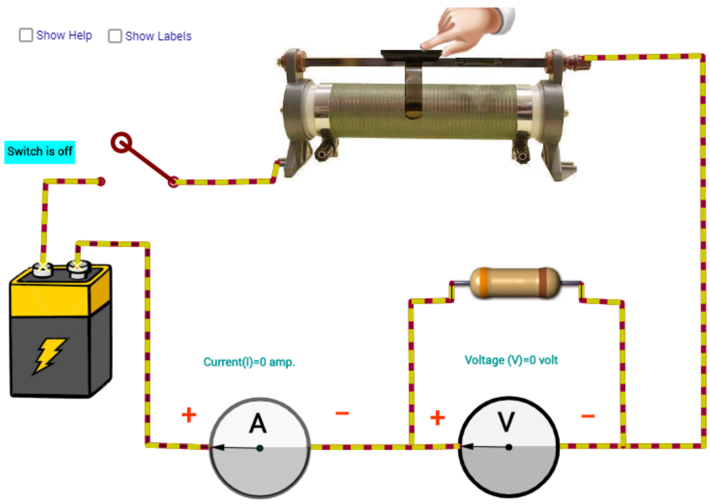


The structured version, the case of Ohm's Law activity: The activities versions were developed to the structured version, the prospective teachers discussed the structured inquiry activities and adopted them without much hesitation. Through this version, we observed some changes in prospective teachers' perceptions regarding the designing of the activities. They expressed their opinion that if the teacher does not pass directly the scientific rules, then he should write detailed procedures for the students to follow, so that they arrive with the help of the directions in the procedures at the rules. One of the prospective teachers said: "Students should be given exact directions if they were to arrive alone at the scientific rules. Though I doubt that they will arrive alone at the rules, even with detailed directions, especially those with moderate or weak abilities, I think we need to verify in the classroom how the students work with those activities.

[1] https://phet.colorado.edu/en/simulation/ohms-law

The structured activity that was suggested by one of the groups for the Ohm's law was the following:

Work with the simulation below the from the Online Labs site[2] to answer the following questions:



- Describe the phenomenon represented in the simulation above.
- Notice the change in the electric circle that results from changing the slider of the voltage? Prepare a table of pairs of values that describes the three values in the electric circuit when the value of resistance is constant.

Current in mA	Resistance in Ω	Voltage in V

What do you conclude from the table above?

- Notice the change in the electric circle that results from changing the slider of the resistance? Prepare a table of pairs of values that describes the three values in the electric circuit when the value of voltage is constant.

Current in mA	Resistance in Ω	Voltage in V

[2] http://cdac.olabs.edu.in/?sub=74&brch=9&sim=75&cnt=4

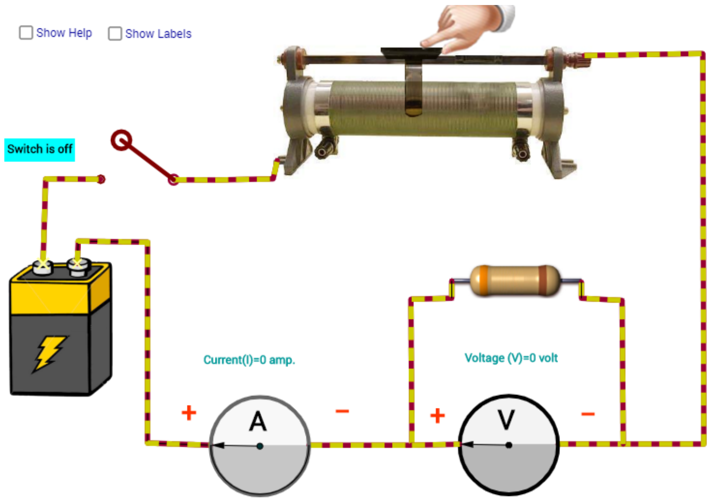
What do you conclude from the table above?

- Write the voltage in an electric circle as an algebraic relationship (equation) between the current and the resistance.
- Write each of the current and the resistance as an algebraic relationship (equation) between the voltage and the third electric component.

The guided version, the case of Ohm's Law: The guided versions were developed by the prospective secondary teachers with the assistance of the lecturer. The prospective teachers discussed the guided inquiry activities but they did not perceive it as applicable in the classroom. Though they were positive regarding their students' learning with STEM activities, they were positivist regarding this learning, for they still thought that their students may find these activities hard to use. This was clarified by one of the prospective teachers who claimed: "it is hard for my students to work with such activities. Sometimes they find scientific rules hard to understand even when I explain the rules thoroughly, so I expect that giving them vague directions will not help them to arrive at the rules alone".

Together with the lecturer, the group wrote the following guided-version activity for Ohm's law:

Work with the simulation below in the Online Labs site[3] to investigate the phenomenon of the current, resistance and voltage. What scientific rules work here?



Do we need mathematics here? What mathematics do we need? How did the mathematics help us?

The open version, the case of Ohm's Law: the open versions activities were also developed with the assistance of the lecturer. Although the prospective teachers discussed the open version activities, they were of the opinion that these activities are meant for the scientists only. These positivist opinions were presented in their discus-

[3] http://cdac.olabs.edu.in/?sub=74&brch=9&sim=75&cnt=4

sion, as clarified by one of the prospective teachers who said: “Only scientists and mathematicians can notice scientific or mathematical phenomena and use scientific tools in order to find a theory that fits these phenomena”. Discussing these activities further, and with the support of the lecturer, the group arrived at the following open version activity:

Study the phenomenon of current, resistance and voltage and find out whether a relationship exists between them. Try to use different tools to study this phenomenon. What are the mathematical tools that can help study this scientific phenomenon?

We now turn into analyzing the prospective teachers’ consideration of the level of integration of the STEM subjects in the activities that they designed.

The level of integration of the STEM subjects in the designed activities: The prospective teachers discussed, together with the instructor, the types of the integration of the subjects in STEM activities. They also attempted, in groups, to write activities from the different types. In fact, after they wrote the above activities, taking care of the inquiry type, they discussed which integration types these activities satisfy and how to turn them into other integration types. The prospective teachers were of the opinion that it is difficult to write activities from the third and fourth integration types. One prospective teacher said: “Though writing STEM activities from the guided version or the open version is not easy, writing STEM activities according to the inquiry type is easier than writing these activities according to the integration type”.

In spite of the prospective teachers’ opinion that writing activities according to the third and fourth integration type is difficult, they stated that the secondary student could manage these types if their inquiry type was the confirmation version or the structured version.

4 Discussion

The present chapter has two aims. First to suggest a theoretical framework that could help to design and evaluate STEM activities and, second, to report prospective teachers’ design of STEM activities according to the suggested framework which included a couple of criteria: the inquiry type and the integration type. As to the first aim, Table 1 describes the suggested framework.

Table 1. The design framework

	Confirmation version	Structure version	Guided inquiry version	Open inquiry version
Combination of two subjects with one dominant subject				
Combination of three or more subjects with one dominant subject				
Combination of two dominant subjects				
Combination of three or more subjects with at least two dominant subjects				

As to the second aim of the present chapter, the findings indicated that according to the inquiry dimension the prospective teachers succeeded in the confirmation version and the structure version but they found it difficult to write the activities according to the guided inquiry version or the open inquiry version. Moreover, they wrote according to the first and second level of integration but they found it difficult to write activities according to the third or fourth integration types. These difficulties reflect that the prospective teachers did not consider, in their designing, the characteristic features of STEM disciplines as forms of human knowledge, inquiry and design, which considered one component of STEM literacy [9]. The difficulties of the prospective teachers are expected since these prospective teachers come from the engineering field and have not participated in pedagogic or didactic courses before in the frame of teacher education programs in which the discussion of pedagogic issues is taking place [4]. The prospective teachers overcame their difficulties with the writing process through discussions as community, between themselves on one hand, and between them and the instructor, on the other hand. This implies the effective and positive role of community in the prospective teachers' learning [29]. Through participating in the discussions and collaboratively designing the STEM activities, the prospective teachers became part of a teachers' community whose shared enterprise is to design STEM activities, taking into consideration a couple of criteria that need to be characteristics of STEM classroom activities. The findings obtained from the class discussions with the prospective teachers about the four inquiry levels reveal that they accepted the first and second levels of inquiry, as means for learning and teaching, but found the third and fourth levels to be difficult for secondary students, which means they did not expect their students to construct their knowledge on their own. These opinions of the prospective teachers reveal positivist beliefs about learning [30]. We argue that the perceptions of the prospective teachers who participated in the current study, related to the level of inquiry needed in the STEM activities, and which appeared in their design of these activities, could affect the effectiveness of the STEM integration, because utilizing STEM integration would be effective when emphasizing inquiry-based instruction [31]. The first two levels of inquiry; i.e. the confirmation version and the structured version, adopted by the prospective teachers, could not provide high quality scientific inquiry. This claim is supported by ref. [2] that argues that deep investigation of the problems in an activity by students is required before engaging in the engineering design process to solve problems [2].

Regarding the integration of the subjects in STEM, ref. [32] points out that many reports claim that STEM could be a context for fostering mathematical skills, where they do not acknowledge the ways in which mathematics can foster the understanding of the ideas and concepts of other STEM disciplines. It could be claimed that in the mathematics classroom, the science, technology and engineering subjects are utilized to serve the development of mathematical concepts and relations. The same is true for the science and engineering classroom, where they both could benefit from mathematics and technology. In the case that we report, the dominant subject was electricity, but an attempt was made that mathematics turns into a dominant subject too. This attempt was partially successful for the STEM activities touched the mathematics but did not approach its concepts thoroughly. This could be explained by the fact that the prospective teachers who designed the STEM activities came from Electronic Engineering and were teachers of electricity in the high school, so it was only natural that they make the electricity concepts dominant in the STEM activities. Similar findings were reported, among science teachers, by ref. [13], where these teachers designed a STEM activity that lacked integrating and communicating mathematics. The challenge of STEM integration by teachers is reported by several researchers (e.g., [33]). These difficulties could be due to the lack of guidance about how to integrate STEM subjects meaningfully. Ref. (e.g., [33]) point at the need for professional development intervention for STEM teachers, which could provide them with tools for developing STEM lessons. Moreover, the current study's findings come in line with ref. [10] that argues that even after students are interested and actively engaged with the technological activity, the challenges remain in getting them to think about the mathematics at a deep level.

5 Conclusion

The present chapter suggests considering the design of STEM activities according to a couple of criteria: the inquiry type and the integration type. Previous research has been paying attention generally to only one of these criteria ([14], [22]) as related to the design of STEM activities. Some researchers mentioned the two criteria as needed in STEM education. Ref. [2] says that engaging students in high quality STEM education requires both the integration of subjects and the method of inquiry in the STEM activities. We claim that considering both criteria adds to the design of STEM activities two perspectives that researchers valued as essential for learning activities: Interdisciplinary learning and inquiry learning. Ref. [34] says that from project evaluations show that interdisciplinary enrichment activities have positive effects on learners' attitudes towards STEM and their interest in it. In addition, ref. [2] says that STEM education could promote inquiry through the process of asking questions and conducting investigations, which could result in a deeper understanding of real world phenomena. We argue that the two suggested criteria could be utilized in the actual design of STEM activities, and in fact not only in this design, but also could be utilized for the evaluation of such activities. So, the two dimensions of STEM activities serve two targets at the same time.

In addition to the above, the present chapter intended to study the prospective teachers' perceptions of the designing and writing processes of the STEM activities. As mentioned above, the prospective teachers found it difficult to design and write the activities according to the guided inquiry version or the open inquiry version. It could be argued that the prospective teachers' epistemological beliefs about how knowledge is construed made it difficult for them to accept that guided inquiry version or the open inquiry version could lead their students to develop understanding of scientific or mathematical concepts. Ref. [35] says that the epistemological beliefs are linked to the types of classroom instructional strategies; i.e. classroom practices of teachers. Moreover, in spite of the prospective teachers' beginning epistemologies about the construction of knowledge, we witnessed that these prospective teachers developed their epistemologies, but not to the extent that they left their previous epistemologies and adopted more progressive one. For teachers, the change in epistemological beliefs about knowledge is not an easy process [36] as it is correlated to a shift in the philosophy of learning [37]. Thus, the process of becoming progressive teachers could be a long process, but it could be claimed that the journey towards adopting a progressive educational approach began for these prospective teachers.

The research findings also showed that the prospective teachers found it difficult to design and write activities according to the third or fourth integration types. Here, the teachers found difficulty in designing an activity that develops concepts related to more than one discipline. Here too, the prospective teachers' epistemological beliefs made it difficult for them to perform such design, for teachers generally believe that mathematical concepts and skills help develop scientific ones. The question is asked how to contribute to the advancement of the prospective teachers' epistemological beliefs and their practices regarding STEM activities. These prospective teachers need more accompanying by supervisors or through workshops that discuss the design of STEM activities depending on the two criteria suggested in the present chapter. In other words, our findings emphasized the challenge in integration between the subjects of STEM. So we agree with [2] that there is a need to enhance the knowledge of STEM among teachers of STEM by their participating in quality professional development. In addition, we followed recommendation to the need for curricula that integrate STEM contexts for teaching disciplinary content in meaningful ways [31].

To continue with the previous argument, STEM education and instruction would be enhanced if teachers have adequate content knowledge and pedagogical content knowledge [33]. Moreover, special attention should be paid to teachers and prospective teachers' perceptions of STEM integration, for they influence the way they design and implement their STEM integration activities [32]. Professional development workshops would, as emphasized above, increase the participants' pedagogical content knowledge, which would affect positively the participants' beliefs about teaching. This would lead to designing STEM activities with high level of inquiry and high level of integration.

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