Introduction to the papers of TWG26: Mathematics in the context of STEM education

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TWG26 met for the third time, this time virtually, at CERME12 and we continued the work started at CERME11 and the virtual Pre-CERME12 Event. At CERME12, 14 papers and 4 posters coming from 10 countries were presented and discussed in order to make STEM (Science, Technology, Engineering, Mathematics) subjects more relevant to students and teachers. The papers and posters were grouped under four themes: (1) M in STEM/STEAM, (2) designing for students learning, (3) processes in STEM/STEAM, and (4) STEM/STEAM professional development. Since the themes are intertwined, each paper could be assigned to multiple themes. Therefore, the assignment of papers to themes was guided by a "best fit" approach as well as practical considerations. As some of our headings below suggest, we sought research on the broader category of STEAM with little success. Thus, the headings represent the thematic areas of our conference call but with very little representation of the Arts in each category. The ideas and issues in the papers and posters will be presented under these four themes in the upcoming parts.

Thematic areas

M in STEM/STEAM

Within this theme three papers were presented. The first paper by Larsen, Kristensen, Seidelin and Svabo examined the role of mathematics in 19 developed STEM activities within the context of the framework developed by Kristensen et al. (2021). The framework based on Kristensen et al.'s review of 37 papers indicates that mathematics can be applied as a tool or can be regarded as a goal in STEM activities in different ways. The investigation of the activities reveals that the role of mathematics as a tool in these activities is to help the students develop an understanding of science or technology or help them in engineering and design processes. The role of mathematics as a goal in these activities is about the development of students' mathematical skills and knowledge. Actually, both need to be considered together as they work together in some way. They cannot be separated from each other. Mathematics sometimes can be a tool or a goal depending on the complexity and the aim of the task, a teacher's (and/or researcher's) goal, and so forth. Mainly, it is important to understand what happens in each moment in a complex task. The discussion of the papers raised several questions moving toward CERME13:

- What are the roles that mathematics plays in STEM activities?
- How can we make learning mathematics as a goal besides using mathematics as a tool in STEM activities?
- What can STEM activities do for the subject of mathematics?
- What can mathematics do for STEM teaching?

The second paper by Bennett and Ruchti analyzed students' interactions in one classroom in which they watched and discussed a video report from the National Oceanic and Atmospheric Administration on the winter outlook for the region. They also analyzed field notes from lesson planning meetings and notes from post-lesson discussions on the base of three of the nine commonly accepted perspectives for defining STEM outlined by Bybee (2013). These three perspectives are 1) simultaneous infusion, 2) temporary shift in discipline, and 3) lateral concept connection. Simultaneous infusion uses mathematical and scientific habits of mind and practices, such as the importance of using data and communicating ideas (e.g., seeing connections between the ways behavior scientists and mathematicians engage as they investigate and attempt to make sense of real-world phenomena). A temporary shift in discipline is a shift from one discipline (e.g., science) to conceptually explore a skill in another discipline (e.g., mathematics), and then a shift back to the original discipline (science) to bring new understandings to the primary science focus. Lateral concept connection is a purposeful movement between two seemingly unrelated core ideas of the same discipline (e.g., the earth science study of weather and the biological science study of birds). The discussion addressed several important questions moving toward CERME13:

- Where is the place for appropriate STEM integration? (curriculum, assessment, instruction)?
- What are the frameworks for appropriate STEM integration?
- How best to link and leverage cross-curricular learning for authentic STEM integration?
- What are the factors contributing to teachers' STEM integration? (e.g., shifting from teacher-directed pedagogy to the more student-directed nature of an integrated curriculum, the structures of school schedules, finances, strict-level or course-level curriculum, school and teacher's knowledge about what STEM is, conception of STEM education, state of anxiety and insecurity, etc.)?

The last paper by Costa and Domingos aimed to examine an experienced Mathematics and Natural Sciences teacher development and implementation of mathematical tasks (e.g., each student infects two colleagues, each student infects three colleagues, etc.) in a mathematics classroom within the context of the COVID-19 pandemic in order to highlight the role of mathematics to understand them. These tasks raised awareness and understanding about the need for measures in the context of the COVID-19 pandemic, such as social isolation or vaccination. Regarding mathematics, powers, exponential growth, variables, iteration, functions, graphics, organization of tables, and data visualization needed to be used and understood. The discussion of this paper in the TWG raised several important issues moving toward CERME13:

- Where should we leave the STEM integration? Are we going to force this "integration" into the mathematics classroom? Into the science classroom? Into the disciplinary course?
- What are the nuances, challenges, and affordances for teachers in developing/implementing STEM tasks for/in their classroom?
- Was there anything that was more difficult?
- What is the role of M in STEM in order to innovate and improve mathematics teaching?

Designing for students learning

The second theme of the submissions involved research related to designing STEM learning environments for students. Two papers focused on the meaning of mathematical models in supporting students' learning while the third investigated students' understanding of already-created models: graphs of linear functions. Regarding the modelling theme, Haier, Siller, and Vorhölter presented a framework of criteria to guide curriculum design involving Education for Sustainable Development. They introduced the notion of socio-critical modeling which refers to the activity of reflecting on one's world critically, organizing social problems mathmatically, and recognizing the role of mathematics in making the world a better place. By merging the criteria of two similar modeling design traditions and paying particular attention to socio-critical aspects, they suggested a set of eight modeling design criteria.

For their part, Just and Siller used literature on models as black boxes in mathematics, science and the work place to develop meaning for black boxes in mathematics. The term *black box* generally refers to a system of relationships, say mathematical, that is often unseen or unknown by the user. Using their carefully crafted definition, they explored ways to integrate modeling with black boxes in mathematics education using a chemistry context. They argued that designing activities to support the opening of black boxes in mathematics education is integral to the modeling process.

Finally, Knippertz, Becker, Kuhn, and Ruzika explored the ways in which students make sense of graphical models and the implications this has for designing instruction on linear function. They used eye-tracking technology to investigate what characteristics of kinematic and mathematical graphs students pay attention to and if their gaze is drawn to different areas depending on the graph type. Their findings confirmed other studies that conclude interpreting kinematic graphs is more difficult than those that are more mathematical in display.

These three papers left us with important questions moving toward CERME13.

- What are design principles specific to supporting students' modeling and socio-critical modeling more specifically?
- How do we leverage real world situations that span the S-T-E- and M disciplines to design students' STEM learning?

Processes in STEM/STEAM

The third theme of the submissions involved research related to understanding the learning processes of students in STEM/STEAM environments. Two papers and one poster explored a variety of ideas within geometrical and spatial sense making. One paper presented a theoretical argument for an extended definition of spatial thinking within STEM, and a final paper challenged current research that suggests reading and mathematical understandings are related.

The first three research projects within the geometry domain shared findings from work with students situated within classroom teaching environments involving geometrical and spatial reasoning. Eckert and Sjödahl, for example, described the tension between providing elementary students simple coding with too much structure (i.e., pre-made codes) and not enough structure, in geometry tasks, with the aim of promoting computational reasoning. Those students who arrived at a solution fairly quickly did not engage in the process of formulating problems whose solutions could be manifested in code. Students who got stuck in their unhindered exploration did not have the supports they needed to decompose the problem situation into more manageable subproblems. Eckert and Sjödahl's findings suggest that tasks need more built-in supports to promote breaking problems into smaller, more manageable pieces.

Ubuz and Aydınyer, for their part, used a Project Based Learning (PBL) approach to support students' development of geometrical reasoning as the students engaged in the engineering design process. They presented the results of a study in which 13–14 years old students re-designed a local neighborhood by first defining the engineering problem, exploring solutions by interviewing family and community members, selecting solutions and creating scaled drawings of the buildings, streets, and other structures. Ubuz and Aydınyer concluded that designing a two-dimensional scale plan of a neighborhood through PBL can strengthen students' knowledge of the engineering design processes while also developing their spatial reasoning. Furthermore, throughout designing a neighborhood plan, they learned how to design a place, the different types of professions and their duties, how to use a protractor to draw geometrical shapes, how to solve the challenges and difficulties as a group, the importance and value of geometry in real life, how the elements of a neighborhood are placed in it, and the importance of every detail such as accuracy and precision in drawings.

Lasa et al. presented a poster that documented a STEM project in which 13–14 years old students must build and calibrate an electronic weighing machine to contextualize the concept of linear functions. They found that the use of a dynamic, geometry software program was a powerful instrument for supporting students' modelling in STEM contexts because students have the opportunity to test any number of attempts before they move to a definitive physical construction. They concluded that it is not only possible, but powerful to use technology to engage students in mathematical reasoning as a primary activity rather than simply as a tool to do the work of the other disciplines (science, technology and engineering).

Zöggeler presented a more theoretical paper exploring the meaning of spatial reasoning and its location within the STEM curriculum. Critiquing current conceptualization of spatial research, they argued that most research has explored students' spatial sense in purely psychometric terms with little attention to problem solving contexts. They introduced an extended model of spatial thinking in STEM that includes two overarching facets, *spatial problem solving* and *spatial* *memory*, with six more elaborate characteristics within those. They argued for the promotion of extended spatial thinking through mathematical, physical and technical contents as well as the promotion of spatial thinking in STEM subjects.

Finally, Cascella shared the results of a study that delved deeper into the relationship between students' reading and mathematics ability. While research has shown that there is a strong relationship between students' reading and mathematical reasoning, studies rarely account for the possible intersectionality between such a relationship and other contextual variables and/or students' personal characteristics. Cascella's research results confirmed that an integrated, interdisciplinary teaching approach is necessary and can be instrumental and powerful to fight educational inequalities across gender, socio-economic status, and citizenship.

These papers left us with important questions moving toward CERME13.

- If there is something called STEM-thinking, what would it encompass?
- What are the possibilities and challenges in talking about STEM-abilities and which abilities are addressed?

STEM/STEAM professional development

The fourth theme of the submissions involved research focused on STEM/STEAM Professional Development. The four papers and the three posters leading to this theme explored a number of intertwined aspects of STEM/STEAM Professional Development, including (1) providing a critical overview on the characteristics of STEM professionalism (Møller), (2) exploring the usability of 3D modelling and printing in STEAM education in primary school (Anđić, Ulbrich, Dana-Picard & Laviza), (3) analysing teachers' views on innovative learning activities (Erbasan & Çakıroğlu), (4) documenting mathematics teachers' experience in teaching STEM (den Braber, Mazereeuw, Krüger & Kuiper), (5) developing a STEAM professional development program for training in-service teachers and exploiting the role of mathematics within a secondary STEAM context (Diego-Mantecón, Laso, Diamantidis, Kynigos), (6) detailing the relationship between STEM practices and the development of 21st century skills (Amado & Carreira), and (7) understanding what knowledge promotes the development and implementation of mathematical interdisciplinary practices within the context of STEM education (Costa & Domingos).

In particular, Møller pointed out that in Denmark, curriculum descriptions of STEM competencies do not exist. To fill this gap, Møller developed a 'concept map', based on the review of both academic and grey literature (see Monash University, 2022). So far, Møller identified three main categories to describe STEM competences: (1) computing and visualizing 'everyday' data with computers, (2) finding and solving STEM-related problems, and (3) innovative STEM thinking.

Anđić et al. discussed the usability of modern tools, such as 3D printers, by reporting on STEAM teachers' opinions and attitudes about 3D modelling and printing. Results suggested, on the one hand, that teachers from different subjects can understand differently the usability of these tools and, on the other hand, that 3D printers require a high level of computer knowledge in order to be used effectively. These results call for a reflection about the potentials and limitations of modern tools in integrated teaching approaches, and for specific training.

In line with this, Diego-Mantecón et al. described an Erasmus+ project aimed to examine and overcome the main issues obstructing the implementation of STEAM education in secondary education, by involving teachers and scholars from Spain, Austria, Finland, Greece, and Hungary.

Research reporting on teachers' experience from other countries confirmed the need to focus on STEM/STEAM Professional Development. For example, from Turkey, Erbasan & Çakıroğlu reported on teachers' experience in teaching mathematics within an integrated (STEM) approach: even though subjects integration is explicitly mentioned in the national curriculum, teachers do not consider the integrated approach as the ordinary one, and, as with other papers presented in the same section, teachers complain about a number of obstacles (such as time constraints, lack of teamwork experiences, lack of knowledge and experience, lack of equipment for activities, and so on) hindering the success of integrated teaching.

Similarly, from Netherlands, Der Braber et al. reported on mathematics teachers' experience in teaching STEM. They discussed the appropriateness of mathematics teachers' training to teach Nature, Life and Technology (NLT). According to Der Braber et al., (teaching/teachers') freedom is, at the same time, the keyword to teach NLT successfully but also a risk if/when mathematics teachers are not aware of the learning goals of such courses, or when their background and work experience causes sharp differences (between teachers) in dealing with interdisciplinary objectives. Those who plan and develop professional training should thus be aware of this, in order to better support teachers in dealing with interdisciplinarity and exploiting the role of mathematics in such an interdisciplinary context.

Finally, Amado and Carreira presented and critically discussed the effect on a group of Mathematics teachers' attitudes and perceptions about the integrated approach after attending a professional development program committed to the innovation of teaching practices. Results showed that offering teachers practical tools, ideas, and guidelines to develop an integrated approach positively affects teachers' attitudes towards integrated teaching approaches and their willingness to engage their students in solving a real-world problem, thus confirming the importance, actually the need, to focus on professional development.

These papers left us with important questions moving toward CERME13.

- What are the key competencies for future STEM teachers?
- How do we prepare teachers to teach STEM in ways that are not isolated S, T, E and M?
- How do we help teachers discuss the role of mathematics in STEM?

Conclusion

Each of the papers and posters in the TWG26 were critically discussed in small and whole groups and captured specific aspects of "STEM" from a mathematics education perspective.

From both the small groups and the plenary discussions, STE(A)M seems to be defined as both a stand-alone subject (broader than just the sum of S+T+E and M) and as a “learning environment” within which teachers (and students) can work at the intersection of different (but sharply intertwined) subjects to construct a new learning environment within which actors can develop new, innovative, and critical thinking.

Results from the research presented seem to suggest that working with real problems is the way to combine S, T, E and M. To think about STEM as a unique subject, given by the combination - rather than just the sum - of its components, we should move from an interdisciplinary to a transdisciplinary approach. In this sense, a transdisciplinary approach can help students to develop both knowledge and competence (both theoretical and empirical/practical) not just in S, T, E and M, but in STEM, conceived as a unique subject.

Teachers in different countries employ very different teaching approaches, but the perception of STEM as an integrated subject is rare everywhere. Obstacles hindering a transdisciplinary teaching approach have been reported in some of the research presented, but also emerged in the TWG26 discussions. Among these ‘hindering factors’, in addition to the lack of time, experience, equipment and appropriate teachers’ training, scholars from different countries (such as Portugal, Spain and Italy) also mentioned the absence of enough knowledge, in the public opinion, about STEM conceived as an integrated discipline, thus raising concerns among students’ relatives/parents. All these reflections confirm that teachers from different countries experience similar difficulties and call for a prompt answer/intervention from educational policy-makers, possibly in an international, common perspective.

Research about STEM, from a mathematics education perspective, should thus focus on these criticalities in the attempt to understand, for example, what STEM education is (if there is such a thing), with emphasis on the M; what the characteristics of instructional materials, teaching practices, STEM programs (e.g., classroom implementation and/or school-wide approach) are, and thus what STEM preparation is and how it can support teachers in developing a proper and effective transdisciplinary approach.

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