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Mathematics as the focal point of STEM teaching

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The role of mathematics in STEM teaching is often described as limited or unclear, and more or less always conceived as a tool. This paper examines the role of mathematics in 19 STEM activities developed in the research and development project LabSTEM, the goal of which includes developing STEM activities where mathematics is the focal point. All 19 activities include mathematics, and they target students from kindergarten to lower secondary school. The analysis contains a categorisation of the different roles that mathematics plays in the 19 STEM activities. The results show that teachers manage to present mathematics not as abstract and decontextualised but as integrated and relevant in most of the 19 activities. Nevertheless, there is a persistent tendency for them to place mathematics learning in the background, relegating mathematics to a supporting role in STEM.

Keywords: STEM education, role of mathematics, 21st-century skills.

Introduction

As STEM teaching has advanced from being mostly a political goal in many countries to gradually becoming a larger and richer component of the classroom. It is important to consider and reflect on the role that mathematics plays or should play in STEM teaching. The acronym STEM does not automatically mean that all four disciplines (science, technology, engineering and mathematics) are included in teaching activities or are included to the same degree. There is no widely accepted agreement on whether STEM education refers to the promotion of knowledge *within* its individual disciplines or an *integrated* interdisciplinary approach. The disciplines can be combined and integrated in various ways. Some scholars argue that even if only two STEM disciplines are included, they are sufficient to constitute STEM teaching (Stohlmann, 2019). Other scholars contend that mathematics is a critical component of any teaching activity labelled STEM teaching (Doğan et al., 2019).

STEM teaching is often described as having a dual purpose. It must both provide students with the skills to perform tasks in complex and interdisciplinary contexts *and* ensure increased competency and skill level in STEM subjects (Maass, 2019). This dual goal poses the risk of a deep understanding of individual subjects being overshadowed by interdisciplinary, context-driven ways of working. Furthermore, a specific concern in the literature is that mathematics, in particular, will not occupy a distinct position because it figures as a background subject in STEM teaching (Shaugnessy, 2013), and STEM approaches seem to have a less positive impact on mathematical outcomes than science outcomes (Honey et al., 2014).

Consequently, the objective of the Danish development and research project, Laboratory for Integrated STEM (LabSTEM), is to develop STEM teaching activities where mathematics is in focus.

The aim is for teachers to balance between addressing real-world problems that students perceive as interesting and relevant and ensure that they do meaningful work with content, skills or methods from mathematics in combination with the other three STEM areas. In this paper, we ask the following research question: RQ: How can mathematics be integrated as the focal point of STEM teaching?

Different ways of integrating mathematics in STEM activities

In the literature, the relation between mathematics and STEM can be understood in various ways (Bybee, 2013). The question that mathematics teachers often ask is what STEM-integrated activities can do for the subject of mathematics. One of the answers is to make mathematics content and teaching more meaningful and relevant by creating a scenario or context for mathematical problem-solving. However, we also need to ask what mathematics can do for STEM teaching. Science provides mathematics with interesting problems to investigate, and mathematics provides science with powerful tools with which to analyse different scientific problems and concepts; thus, the relationship is reciprocal (Fitzallen, 2015).

Pang and Good (2000) reviewed studies that integrated mathematics and science in the 1990s and stated that, at the time, the dominant approach focused primarily on scientific content, with mathematics assuming a supporting role. The authors even posed an interesting question, which remains relevant today: Is the focus on science a much more natural and productive approach for integration? In contrast, Isaacs et al. (1997) suggested that mathematics should form the primary basis of the integrated curriculum because of its inherently logical structure. Other researchers have pointed to engineering as a good starting point for integrating mathematics into STEM activities (Berland & Steingut, 2016). Bennet and Ruchti (2014) suggested the integration of mathematics into STEM activities using mathematical practices as a common framework, and several scholars have also described mathematical modelling as a way of integrating the disciplines, thereby making mathematics the focal point (Auning, 2021; Doğan et al., 2019; Maass et al., 2019).

Kristensen et al. (2021) developed a framework describing the various roles that mathematics can play in STEM activities. The framework is based on the authors' review of 37 papers, all of which included different STEM activities in which mathematics was integrated.

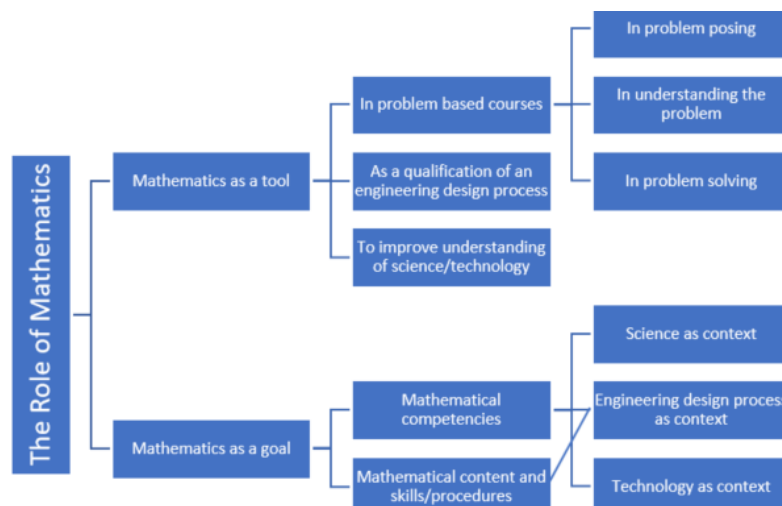


Figure 1: The role of mathematics (Kristensen et al., 2021)

The framework in Figure 1 shows that mathematics can be variously applied as a tool in STEM activities, for example, to qualify an engineering design or improve students' understanding of a specific science. When mathematics is a tool, mathematical skill, contents and competencies are not the focal point of the activity; however, mathematics is included, for example, to solve a problem in science or to develop something in engineering processes. Students do not necessarily learn new mathematics concepts/competences, but they are able to see that their mathematics knowledge can be used in other contexts. Figure 1 also shows that mathematics can be regarded as the primary objective and aim in a STEM activity, for instance, to develop students' mathematical skills and conceptual understandings of mathematics or mathematical competencies (Niss & Højgaard, 2011). When mathematics is the goal, students' learning of mathematics in the activity must be made clear. In these activities, science/engineering/technology is the context for mathematics learning. Mathematics can simultaneously serve as a tool and a goal in specific learning activities, and therefore, the dual roles are not mutually exclusive. More follows on this below.

LabSTEM – mathematics as the focal point of STEM

LabSTEM is a three-year research and development project which began in January 2020. Its purposes are to develop a STEM approach to teaching that is tailored for Denmark and to make it available for teaching and learning practice in order to support sustainable and interdisciplinary STEM teaching from day care to secondary school. Organisationally, temporary communities of practitioners and researchers were established in the form of STEM laboratories. These are not actual, physical laboratories but event-based gatherings of people. In 2021, 17 such laboratories were established, with approximately 250 participants, including kindergarten, primary and secondary school teachers. The aim of these laboratories is for teachers to develop STEM-teaching activities, with mathematics as the focal point. Furthermore, the aim is for these activities to be empirically tested in practice, with guidance from lecturers/researchers from university colleges or the University of Southern Denmark. Throughout the first year, the laboratories developed 19 STEM teaching activities, which we analyse in detail in this paper. These activities explicitly describe how mathematics is included and demonstrate noticeable differences in the ways in which they present mathematics. It is noteworthy that among the participating teachers, some were mathematics teachers, others were science teachers, and many were both.

Methods

The STEM activities were developed in teams of two to six members in the different laboratories. Afterwards, the teachers described each activity, including its title, level, theme, duration, prerequisites, relation to the national curriculum, goals, assessment, the learning process and how the different disciplines (S, T, E and M) operate. The 19 activities were then coded by the first and second authors of this paper in an Excel spreadsheet under different categories: mathematics content from the course description; how mathematics is applied, including a description of student work; a short

description of the teaching activity and a description of which STEM discipline was included and its focus. The research group then discussed each activity in relation to the model of Kristensen et al. (2021) (see Figure 1). In this paper, our analysis of the 19 activities is not based on empirical observations from classrooms; it is based exclusively on the teachers' course descriptions.

The 19 activities come from different levels of the school system: two from kindergarten, 12 from primary school and five from lower secondary school. This distribution pertains to the fact that the majority of the STEM laboratories are at the primary school level. The STEM activities deal with myriad contexts, from designing homes for hedgehogs to sorting waste or growing potatoes. A table of the 19 activities can be accessed here: <http://kortlink.dk/2dv9k> (each of which is numbered; these numberings will be used in this paper). The first two authors of this paper jointly conducted the analyses and categorisations of the different activities. Each activity description was read and discussed with regard to the different categorisations in Figure 1. In the following sections, we first describe one of the activities to clarify our analytical approach, followed by an overall analysis of the 19 activities.

Case – germination and growth of sunflowers and watercress

A first-grade activity called Plants and Germination was developed in one of the laboratories. The focus was on sunflowers and watercress and what their seeds needed in order to grow. The activity began with a walk in the woods, focusing on observing normal conditions for the plants in the forest. Each student was then given a sunflower seed to embed in a cotton ball in a plastic bag, each of which was then taped onto the classroom window, resembling a cardboard greenhouse (see Figure 2a). Each student then kept a schedule of how many millimetres the plant grew from day to day. Additionally, watercress seeds were sown in milk cartons (see Figure 2b), which were positioned in different places in the classroom, with or without light and with more or less water.



Figure 2. Pictures of growing seeds: a) sunflower; b) watercress

In the days that followed, the students observed and documented the seed germination. How many watercress seeds sprouted? By how many millimeters did the sunflower seeds grow per day? The students systematically reported their results on Excel spreadsheets. Clear descriptions were provided that specific focus had to be placed on measuring with a ruler and the concept of measurement. The purpose was to make groups of students find some patterns showing the best conditions for the seeds. At the end of the activity, the students held dialogues in class and then in groups about their results and prepared a short video where they used their data to explain their results while showing the seeds and plants.

The following target outcomes for mathematics are listed in the course description: i) “The student can make a statistical inquiry with simple data”. ii) “The student has knowledge of simple methods of collecting, arranging and describing simple data”. iii) “The student has knowledge of and can measure units of length” (English translation). Based on the model (Figure 1) of Kristensen et al. (2021), we identified the role played by mathematics in this activity. First, we observed that mathematics was used as *a tool* to develop the students’ scientific understanding of photosynthesis. By measuring the sprouts with a ruler, the students learnt more about what the seeds needed to grow. Second, mathematics was a specific *aim* of the activity. As stated in the course description, one of the target outcomes was the development of the students’ mathematical skills (by using a ruler) and knowledge about the concept of measurement (as described, e.g. by Lehrer, 2003).

The role of mathematics in the 19 STEM activities developed

Similar to the case discussed in the preceding section, we examined the 19 above-described STEM activities from year one in LabSTEM. In almost all the activities, mathematics was used as *a tool in the STEM activities* (see Table 1). In relation to our RQ, this means that the role of mathematics in these activities was to help the students develop an understanding of science or technology or help them in engineering and design processes. Only in one activity was mathematics not defined as a tool (activity 16). Here, it was the main aim; the focus was on pi and the symbol’s history and meaning in everyday life.

Mathematics as a tool and the aim of the mathematics (activity number is in parentheses)					
In problem-based activities	To qualify an engineering /design process	To improve understanding of science	To improve understanding of technology	To improve understanding of technology <u>and</u> science	To improve understanding of engineering <u>and</u> science
(6,17,18)	(2,3,4,5,13)	(7,8,10,11,12,15)	(19)	(1)	(9,14)
3	5	6	1	1	2

Table 1: Overview of the role of mathematics in the developed activities

As mentioned earlier, all course descriptions explicitly listed the mathematics-specific goals of the various activities (this was a requirement in the guideline form), but it is important to clarify that we do not know whether the students actually achieved these goals in practice. Moreover, the descriptions were not all clear about how the students would achieve these specific goals.

By studying the mathematics-specific content comprising the explicit aim of the 19 activities, we observed a wide spectrum. It was difficult to judge whether the content was about reviewing known concepts/skills or learning new concepts/skills in mathematics; however, we found a prevalent focus on the application of known mathematics, mostly because the goals described were often included in the curriculum of lower classes. However, in these activities, the students tried to apply the mathematical concepts as tools in other as well as new contexts. Three activities described a specific

focus on problem-solving, but in many of the others, mathematical modelling competence was very central, albeit without this being explicitly described. Often, only the mathematical skills were explicitly written, including practising counting, learning or reviewing skills in measuring time, handling data (e.g. with frequency tables) and measuring length with a ruler. Table 2 below presents an overview.

Mathematics as an aim	
Competence	Skills and concept knowledge
problem-solving	counting, writing numbers, scale ratio, geometric shapes, spatial figures, curves in the coordinate system, concept of functions (slope), measurement, statistics, spreadsheet, time, data comparison, pi, area and volume, angles, economics

Table 2: Mathematics-specific goals in the developed activities

We include statistics as part of mathematics because it is part of the mathematics teaching curriculum at these grade levels. This is despite the fact that these subject areas can also be viewed as separate from each other (Capaldi, 2019). Table 2 demonstrates that it is not accurate to say that some mathematical topics feature more frequently as aims in STEM courses than others as there is no one-sided focus on specific topics.

Discussion and conclusion

Overall, the LabSTEM teachers developed activities in which mathematics is part and parcel of the aim and where the participating students engage with mathematics as a tool to gain a deeper understanding of science/technology/engineering. It is less clear the extent of the role of mathematics as this is not explicitly stated in the LabSTEM activity descriptions.

In many STEM activities, mathematics has no clear role (Kristensen et al., 2021; Martín-Páez et al., 2019). However, in the 19 activities discussed in this paper, mathematics is not abstract and decontextualised. It is clearly part of the activity, and it is relevant and integrated to a greater or lesser degree. Interestingly, when teachers are assigned the specific task of making mathematics the focal point, they almost always use mathematics as both a tool *and* a goal, which leads to the question of whether it is possible *not* to make mathematics a tool in STEM activities (making it only the aim) and still integrate all the disciplines.

To answer the question of how mathematics can be integrated as the focal point of STEM teaching, we argue that teachers need to have a clear focus on this when planning the teaching activity and need a great deal of support if this is to happen. At the same time, mathematics must figure as both a goal and a tool in the activity itself. The kind of tool that mathematics is, however, is an interesting question, and the precise meaning of *tool* could well be up for further research – for example, is tool a language or a context?

The mathematics-specific goals of the 19 activities are widespread, but they are often characterised by reviews of mathematical concepts, skills training or applications of learned mathematics. Gravemeijer et al. (2016) discussed how mathematics may prepare students for the future and argued

for a shift *from* competencies that compete with what computers can do *to* competencies that complement computer capabilities. They suggested a greater focus on developing 21st-century skills such as critical thinking in mathematics, posing mathematical problems and mathematical communication. This is in line with the argument that STEM teaching aims to prepare for 21st-century skills (Maass et al., 2019). There is, however, little connection between the mathematical content that Gravemeijer et al. (2016) proposed and the mathematical content forming the aim of the developed activities. For example, none of the activities have creativity or the posing of problems as aims. However, in addition to the explicitly described mathematical content, other mathematical processes will probably be included when the activities are enacted in practice. Examples include whether students need to make argumentations for their mathematical answers (mathematical reasoning competence) or work with different mathematical representations (mathematical representation competence) (Lim & Seldom, 2010).

An additional theme worth discussing is the clarity of the target outcomes for students. Is it problematic if students are not explicitly told that mathematics competencies are included in the activities? Although we, as researchers in mathematics education, can perceive mathematics as central, it is probably more doubtful that all students will be cognisant of this. In this case, therefore, the activity would not help solve the problem of viewing mathematics as abstract and isolated from students' everyday life (Niss & Højgaard, 2011).

One of the tendencies of working with integrated STEM activities is to relegate the specific subjects to the background and bring the case/problem to the fore (the problem, rather than the subjects, as the aim) (Klausen, 2011). This may form the basis of critical reflection towards our own study since, in one sense, it contains a degree of "silo thinking": focusing on mathematics in integrated activities. Nevertheless, if the most important part of mathematics is invisible to students, there is a great risk that they will not experience the significance of these competencies. Obviously, the teachers in the LabSTEM project do not present mathematics as abstract and decontextualised but as integrated and relevant in most of the 19 activities. In many ways, however, they are still inclined towards pushing mathematics learning to the background, relegating it to a supporting role as a tool in the STEM context rather than important in its own right.

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