Mathematics as the focal point of STEM teaching

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The role of mathematics in STEM teaching is often described as small and unclear and more or less always as a tool. This paper examines the role of mathematics in 19 developed STEM activities in the research and development project LabSTEM, whose goal is (among other things) to develop STEM activities where mathematics is the focal point. All 19 activities include mathematics and are directed to students from kindergarten to lower secondary school. The analysis contains a categorisation of the different roles that mathematics play in the 19 STEM activities. The results show that the teachers manage to present mathematics, not as abstract and decontextualised, but integrated and relevant in most of the 19 activities, but they still tend 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 classrooms, it is important to consider and reflect on what role 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. There is no widely accepted agreement on whether STEM education refers to the promotion of knowledge *within* its individual disciplines or to an *integrated* interdisciplinary approach. The disciplines can be combined and integrated in many different ways. Some scholars argue that even if just two disciplines in STEM are included, these are sufficient to constitute STEM teaching (Stohlmann, 2019). Other scholars contend that mathematics must be included in order for a teaching activity to be labelled STEM teaching (Doğan et al., 2019).

STEM teaching is often described as having a double purpose. It must both provide students with the skills to perform tasks in complex and interdisciplinary contexts *and* ensure increased competency and skill levels in the subjects that constitute STEM (Maass, 2019). This dual goal poses the risk of a deep understanding of individual subjects being overshadowed by the interdisciplinary context-driven ways of working. Furthermore, a specific concern in the research literature is that in particular, *mathematics* 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 teaching and learning (LabSTEM), is to develop STEM teaching activities, where mathematics is in focus. The aim is for teachers to balance between addressing real-world problems, which students perceive as interesting and relevant, and ensuring that the students do meaningful work with content, skills or methods from mathematics in combination with the other three areas of STEM. In this paper, we ask this research question:

RQ: How can mathematics be integrated as the focal point of STEM teaching?

Different ways to integrate mathematics in STEM activities

In the literature, the relation between mathematics and STEM can be unfolded in many different 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 the teaching and content of mathematics 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 to use in analysing different scientific problems and concepts; hence, the relationship is reciprocal (Fitzallen 2015).

Pang and Good (2000) reviewed studies that integrated mathematics and science in the 1990s and stated that the dominant approach at that time had science content as the main focus, with mathematics in a supporting role. They even posed this interesting question that 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 point to engineering as a good starting point for integrating mathematics into STEM activities (Berland & Steingut, 2016). Bennet & Ruchti (2014) suggest integrated mathematics in STEM activities using mathematical practices as a common framework and several scholars also describe mathematical modelling as a way of integrating the disciplines and in this way let mathematics be a focal point (Auning, 2021; Doğan et al., 2019; Maass et al., 2019).

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

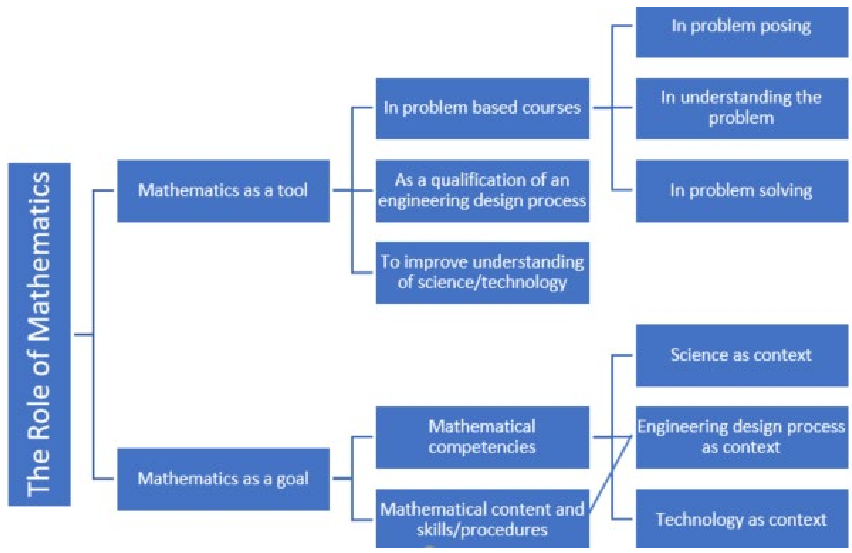

Figure 1: The role of mathematics (Kristensen et al., 2021)

The framework in Figure 1 shows that mathematics can be applied as a tool in STEM activities in different ways, for example, to qualify an engineering design or to improve students' understanding of a specific science. However, it also shows that mathematics can be regarded as the primary objective and aim in a STEM activity, for instance, to develop students' skills, conceptual understanding of mathematics or mathematical competencies (Niss & Højgaard, 2011). Mathematics can simultaneously be both a tool and a goal in specific learning activities. These two potential roles of mathematics 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 started 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 daycare to secondary school. Organisationally, temporary communities of practitioners and researchers are established in the form of STEM Laboratories. These are not actual, physical laboratories but event-based gatherings of people. In 2020, 10 such laboratories were established, with approximately 130 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. These activities are also intended to be empirically tested in practice. This is done with the guidance of 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. The 19 activities explicitly describe how mathematics is included and demonstrate noticeable differences in the ways that mathematics is presented in the teaching activities. It is noteworthy that among the participating teachers, some were mathematics teachers, and others were science teachers, but many were both.

Methods

The STEM activities were developed in teams with 2–6 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) are in play. The 19 described 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 with which focus. The research group then discussed each activity in relation to the model by Kristensen et al. (2021) (see Figure 1). In this paper, our analysis of the 19 activities is not based on empirical observations from classrooms, but solely on the course descriptions made by the teachers.

The 19 activities come from different levels of the school system: 2 from kindergarten, 12 from primary school and 5 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 many different contexts, from designing homes for hedgehogs, to sorting waste or growing potatoes. A table of the 19 activities can be seen here: http://kortlink.dk/2dv9k. (In this table, the 19 activities are numbered; these numberings will be used in this paper prospectively). The first two authors of this paper made the analyses and categorisations of the different activities jointly. Each activity description was read and discussed with regard to the different categorisations in figure 1.

In the following sections, we first describe one developed activity to clarify our analytical approach, followed by an overall analysis of the 19 developed 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 is on sunflowers and watercress and what their seeds need in order to grow. The activity starts with a walk in the woods, focusing on the observation of the normal conditions for plants in the forest. Each student is then given a sunflower seed that they must embed in a cotton ball in a plastic bag, each of which is then taped on the classroom window, resembling a cardboard greenhouse (see Figure 2a). Each student then keeps a schedule of how many millimetres the plant grows from day to day. Additionally, watercress seeds are sown in milk cartons (see Figure 2b). These are put in different places in the classroom, with or without light, and with more or less water.

Figure 2. Pictures of the seeds growing a) sunflower and b) watercress

Over the following days, the students observe and document the seed germination. How many of the watercress seeds have sprouted? By how many millimeters do the sunflower seeds grow per day? The students systematically report their results on Excel spreadsheets. It is clearly described that there is a specific focus on measuring with a ruler and the concept of measurement. Its purpose is to make groups of students find some patterns that show the best conditions for the seeds. At the end of the activity, the students hold a dialogue about their results in class and then in groups, prepare a short video where they use their data to explain their results while showing their 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 Kristensen et al. (2021) model (Figure 1), we now identify the role played by mathematics in this activity. First, we observe that mathematics is used as *a tool* to develop students' scientific understanding of photosynthesis. By measuring the sprouts with a ruler, the students learn more about what the seeds need to grow. Second, mathematics is a specific *aim* of the activity. As stated in the course description, one of the target outcomes is the development of the students' mathematical skills (by using a ruler) and knowledge about the concept of measurement (as described, for example, by Lehrer et al. (1999)).

The role of mathematics in the developed STEM activities

In the same way as the case discussed in the preceding section, we have examined all the 19 described STEM activities from year one in LabSTEM. In almost all activities, mathematics is used as a *tool in the STEM-activites.* The result can be seen in Table 1. In relation to our RQ, this means that the role of mathematics in these activities is to help the students develop an understanding of science or technology or help them in engineering and design processes. Only in one activity mathematics is not defined as a tool (activity 16). Here mathematics is the main aim; the focus is 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 and science**	**To improve understanding of engineering and 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, all course descriptions explicitly state what mathematics-specific goals are intended in the different activities (this was a requirement in the guideline form), but it is important to clarify that we do not know whether the students actually achieve these goals in practice. Moreover, the descriptions are not all clear about how the students will achieve these specific goals.

If we study what mathematics-specific content is explicitly the aim in the 19 different activities, we observe a wide spectrum. It is difficult to judge whether the content is about reviewing already known concepts/skills or learning new concepts/skills in mathematics, however we find a prevalent focus on the application of already known mathematics, mostly because the goals described are often included in the curriculum of lower classes. However, in these activities, the students now try to apply the mathematical concepts as a tool in other and new contexts. Three activities describe a specific focus on problem solving, but in many of the other activities, mathematical modelling competence is very central without it being explicitly described. Often only the mathematical skills is explicitly written. Examples include practising counting; learning or reviewing skills in measuring time, handling data (e.g., with frequency tables) and measuring length with a ruler. Table 2 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

Statistics is included here as part of mathematics because statistics 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 shows that it is not possible to say that some mathematical topics are more frequent to have as aims in STEM courses than others, as we do not see a one-sided focus on specific topics.

Discussion and conclusion

Overall, the LabSTEM teachers have developed activities, where mathematics is clearly a part and an aim of the activites, and where the partaking students engage with mathematics as a tool to gain a deeper understanding of science/technology/engineering. It is more unclear exactly how large the role of mathematics is, as this is not explicitly stated in the LabSTESM activity descriptions.

In many described STEM activities, mathematics does not have any or a 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. Mathematics is clearly a 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 a focal point, they almost always use mathematics as a tool *and* as a goal. It leads to the question of whether it is possible *not* to make mathematics a tool in STEM activites (but only to make it the aim) and still integrate all the disciplines.

To answer how mathematics can be integrated as the focal point of STEM teaching, we state that teachers need to have a clear focus on this when planning the teaching activity and in addition a great deal of support if this is to happen. At the same time mathematics must be placed both as a goal and a tool in the activity itself.

The mathematics-specific goals in the 19 activities are widespread but often characterised by reviews of mathematical concepts, training in skills or applications of already learned mathematics. Gravemeijer et al. (2016) discuss what mathematics may prepare students for the future and argue for a shift *from* competencies that compete with what computers can do *to* competencies that complement computer capabilities and suggest focusing more on developing 21st-century skills, such as critical thinking in mathematics, posing mathematical problems and communicating mathematics. This fits 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) propose and the mathematical content that has become the aim in the developed activities. None of the developed activities for example has creativity or posing problems as an aim. However, it must be discussed that in addition to the explicitly described mathematical content, there will probably be other mathematical processes included when the activities are enacted in practice. Examples include whether students need to make argumentations for their mathematical answers (mathematical reasoning competence) or need to work with different mathematical representations (mathematical representation competence) or focus on ways of thinking about and doing mathematics (mathematical habits of mind) (Lim & Seldom, 2010).

An additional theme worth discussion, 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 notice this. In this case, nevertheless, the activity does not help to solve the problem of viewing mathematics as abstract and isolated from students' everyday life (Niss & Højgaard, 2011).

When working with integrated STEM activities, it can be a goal to relegate the specific subjects to the background and make the case/problem come 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. On the other hand, if the most important part of mathematics is invisible to students, there is a great risk they do not experience the significance of precisely these competencies. Obviously, in the LabSTEM project, the teachers have not presented mathematics as abstract and decontextualised but integrated and relevant in most of the 19 activities. Nonetheless, in many ways, they still tend to push 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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