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Mette Als Kristensen
University of Southern Denmark, Denmark

Dorte Moeskær Larsen
University of Southern Denmark, Denmark

Lars Seidelin
University of Southern Denmark, Denmark

Connie Svabo
University of Southern Denmark, Denmark

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The Role of Mathematics in STEM Activities: Syntheses and a Framework from a Literature Review

Mette Als Kristensen, Dorte Moeskær Larsen, Lars Seidelin, Connie Svabo

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Abstract

In recent years, science, technology, engineering and mathematics (STEM) approaches in education have received growing attention in the political arena and in educational research and practice. A concern consistently raised in the research literature regarding interdisciplinary STEM education is that the role played by mathematics is understated such that it may be overshadowed by the other disciplines. This study contributes to the discussion by presenting a review of 4,812 studies, of which 37 with descriptions of STEM activities were selected, analysed and synthesised to identify the various roles played by mathematics in these STEM activities. This process produced an analytical framework that captures the various roles mathematics can play, which can be categorised into two major categories: mathematics as the specific aim of the activity or mathematics utilised as a tool. Two cases selected from the review are presented in this study to demonstrate how the framework can be employed in analysing STEM activities. Furthermore, we propose using the framework when developing STEM activities as a tool to ensure explicit awareness of the various roles mathematics can play.

Introduction

Science, technology, engineering and mathematics (STEM) has received much attention in recent years and has been discussed in both the political arena and in educational research and practice globally. Despite this attention, there is no consensus on the meaning of the acronym, which can refer to both monodisciplinary education in the four separate subject areas (i.e., science, technology, engineering and mathematics) or to an integration of two or more of the disciplines (Bybee, 2018). In the research literature, substantial attention has been paid to integrated STEM teaching and learning (English, 2016), and it has been posited that STEM is a potentially promising approach to addressing complex real-world problems using students' disciplinary knowledge and skills (Bybee, 2018). The aim of STEM education is twofold, as STEM should (1) contribute to the development of students' competencies to perform in complex and interdisciplinary contexts and (2) promote knowledge and practices in the individual disciplines that constitute STEM (Maass et al., 2019). With this dual aim, there is a risk of the individual disciplines being overshadowed by the context and problems being addressed, and in the literature, there is a concern that mathematics is moving out of focus in integrated STEM approaches.

Furthermore, Honey et al. (2014) found that STEM approaches appear to have a lower positive impact on mathematical outcomes than on science outcomes, and there is a risk that an inadequate focus on the connections between mathematics and the other STEM disciplines will weaken mathematics learning within STEM activities (English, 2016). There is also a potential risk that mathematics will become less explicit for students, who consequently may not understand its applicability (Shaugnessy, 2013). When adressing real world problems it is important to ensure meaningful attention to content, skills and methods from the individual disciplines—including mathematics.

In the planning and implementation of STEM teaching, the discipline of mathematics can be included in several different ways: as the most important component in the STEM activity, as playing more of a supporting role or as an inserted supplement to the overall problem. We find that it is crucial to consider the different roles mathematics can play in STEM because when teachers know the various possibilities for integrating mathematics into STEM, they make more reflective, nuanced, and explicit choices about mathematics when planning STEM activities. Accordingly, we ask the following research question:
What roles does mathematics play in STEM activities, as described in the research literature?

This study contributes to the inquiry on the role of mathematics in STEM by presenting a framework produced from a systematic review of the research literature describing integrated STEM teaching and learning activities in the target group, from day care to secondary education. We demonstrate the use of this framework with two selected cases and discuss the included studies in light of the framework.

The Role of Mathematics in STEM Approaches

In the literature, there are different perspectives on how the relationship between mathematics and STEM can unfold. Fitzallen (2015) argued for an increased focus on the reciprocal relationship between STEM and mathematics: STEM can be viewed as a context for learning mathematics, while mathematics is also crucial for understanding the ideas and concepts in the other STEM disciplines. Fitzallen (2015) argued further that in the STEM approaches described in the literature, it is common to find STEM activities in which the focus is on using STEM as a context for learning mathematics, while the other approach, with a focus on the role of mathematics in understanding knowledge of the other STEM disciplines, is not often found. It is not enough to acknowledge mathematics as underpinning the other disciplines, and mathematics could be perceived as playing more of a supporting role in integrative STEM approaches if it is only incidentally integrated (Fitzallen, 2015). If the role of mathematics is to be enhanced, a shift in focus from incidental integration in STEM to more explicit integration with a focus on mathematics instrumental nature could be one way to achieve this (Fitzallen, 2015).

Another perspective on how mathematics can interplay in STEM activities is to use real-world contexts and problems, which are most often interdisciplinary and therefore well suited to STEM approaches (Honey et al., 2014). Honey et al. (2014) found that real-world problems are, to some degree, often used in integrated STEM learning activities. Thereby, students have opportunities to apply their disciplinary knowledge and skills to address complex real-world problems in a creative and critical way (Maass et al., 2019). Shaughnessy (2013) also advocated for the use of problem-based approaches in STEM activities, while simultaneously warning that mathematics as a discipline is at risk of becoming silent if denied special attention. Mathematics can play a central role in addressing real-world problems through, for example, mathematical modelling as a way of investigating and solving such challenges (Maass et al., 2019). A focus on mathematical modelling is one way to advance mathematical education within STEM approaches (Maass et al., 2019) due to the inherent relationship between mathematical modelling and the real world. A mathematical model reflects a part of reality that can be analysed through the model (Auning, 2021; Michelsen, 2016).

Another method that can be used to address real-world problems is the application of engineering design processes (Honey et al., 2014), and this method is often used as a vehicle for integration in STEM activities (Stohlmann, 2018). Using an iterative process, the students identify, design, build and test solutions to specific problems, and through this process, they can employ their scientific and mathematical knowledge in a similar way to engineers (Honey et al., 2014). English (2016b) argued that students have the opportunity to create, apply and adapt mathematical concepts when addressing real-world problems through engineering. However, it seems that engineering-based problems tend to be oriented towards science at the expense of mathematics (Honey et al., 2014). Therefore, the challenge is to achieve a more balanced integration of the other disciplines in engineering design processes.

When mathematics is an integral part of STEM, it also changes the focus of the content in mathematics. Traditionally, mathematics has often had an explicit focus on skills and routines (Niss & Jensen, 2011), but Gravemeijer et al. (2017) noted that mathematics education for the future must complement the work that can be done by computers, so mathematical education must focus more on modelling and application. This new focus fits well with the goals of STEM, which are often described as 21st-century skills.

Methods

To answer our research question (What roles does mathematics play in STEM activities, as described in the research literature?), we are guided by the procedure outlined in Petticrew and Roberts (2006). A systematic search, selection and reading of studies was conducted as described in Larsen et al. (2022). First, five databases were selected to ensure that the results were representative of different scientific areas, such as psychology (via PsycINFO), science (via Web of Science), and pedagogy (via EBSCO). In EBSCO, we selected the following databases for searches: Academic Search Premier, Education Resources Information Center (ERIC), MathSciNet and the Teacher Reference Center. In addition, Scopus and ProQuest were included because they provide a broad and global overview of the literature across many different branches of research. We then searched in the databases with the search terms ‘STEM literacy’, ‘STEM education’, ‘STEM learn *’, ‘STEM competen*’ or ‘STEM teach*’ included in the title or abstract, and the search term ‘mathemati*’ included in the body of the text. The keywords were chosen by screening abstracts in special editions of journals that focused on STEM teaching. The publication period considered was January 1, 2015 to March 1, 2020. Only peer-reviewed studies in English were considered.

Removing duplicates from the search results brought the total to 4,812 studies. These studies were first sorted by three different researchers who read the titles and abstracts. The criteria for excluding a study were as follows:

1. Studies with a focus on only one of the four disciplines in the STEM acronym.
2. Studies not dealing with day care, primary or secondary education, i.e., focused on higher education.
3. Studies on STEM in an informal teaching environment, i.e., summer schools, camps or museums.
4. Studies on teaching that requires special equipment or software not available at typical institutions, including studies on specific exclusive robots.
5. Studies with a focus on science, technology, engineering, arts, and mathematics (STEAM).
6. Studies focused on a specific group of students, including specific genders, ethnic minorities, exceptionally intelligent children, or children with special needs.
7. Studies on training pre-service or in-service teachers.
8. Studies on the education policy or governance documents of a specific country.
9. Studies focused unilaterally on students' or teachers' attitudes and expectations regarding STEM teaching.

This review was performed within the context of a specific project called LabSTEM, which is reflected in our exclusion criteria. In the LabSTEM project, we aim for an integrated approach to STEM, which informs the first exclusion criteria. The project is situated in the Danish education system—day care to secondary education—with a focus on ordinary institutions using Danish curricula. This is reflected in the second, third and fourth exclusion criteria. Because we were interested in STEM courses (and not STEAM courses) aimed at all kinds of students in lower education, we also selected the fifth, sixth and seventh criteria as a way to focus our inquiry. Finally, we wanted studies that described STEM teaching and learning and not the policies, expectations and attitudes towards STEM, which informs the eighth and ninth criteria.

To strengthen the reliability of the selection of studies based on a reading of the titles and abstracts, the first 100 studies were sorted jointly. The other studies were then divided into three groups, which were roughly sorted by three different researchers. The studies included by one researcher during this first round were subsequently read by another researcher. These two rounds of reading filtered the number of studies under consideration to 172 (n = 172). Subsequently, reviews, meta-studies and proceedings were also removed, reducing the number of considered studies to 151 (n = 151). These studies were then jointly sorted by the three researchers, with all titles and abstracts from the preceding round read by all three researchers, followed by a discussion of whether each individual study should be included or excluded. After this round, the number of studies under consideration decreased to 84 (n = 84). In addition, a specific search was made in the journals NorDiNa, NOMAD and MONA for an opportunity to include Nordic and Danish studies, which resulted in eight studies, three of which were finally included, bringing the total number of studies under consideration to 87 (n = 87).

The 87 studies were subsequently read in full and analysed, and based on the exclusion criteria, a further 25 studies were excluded, bringing the number of selected studies to 62. This collection was used to analyse and describe perspectives on STEM education, as outlined in the study by Larsen et al. (2022). For an in-depth analysis of different described STEM activities, we selected (from the 62 studies) only studies that contained a specific description of a STEM activity, further reducing the selection to 37 (n = 37), which constituted the study sample (Appendix). The selected studies were cross-read, with special attention given to four new categories: (1) activity description or content, (2) objectives, (3) assessment and (4) mathematics. These categories were then used to analyse the role of mathematics in STEM approaches. The analysis is presented in the next section.

Developing the Framework

Based on the 37 studies in the study sample and the 4 categories given above, an analysis of the role of mathematics was conducted producing a framework for identifying the roles that mathematics plays in relation to other STEM disciplines. The methodological and analytical process which produced this framework is based on the coding of four categories: content, objectives, assessment of the activity, and mathematics for each of the studies included in the review. Before the analysis, three of the researchers individually prepared a short written description of their perceptions of the role of mathematics in the various studies, intended as the starting point of the analysis. This was followed by an abductive analytical process (Brinkmann, 2014): resolving how to make sense of the notion of role and how to create a heuristic that comprehends the different ways in which mathematics can interplay in STEM. This process was facilitated by a fourth researcher as a collective sense-making exercise conducted on two whiteboards.

An outcome of this abductive analytical process was the emergence of two distinct ways to make sense of the role of mathematics. One of these findings: the role of mathematics in relation to the other STEM disciplines, is detailed in this study and displayed in figure 1. The second heuristic concerns the degree to which mathematics is present in STEM activities, which will be communicated in a separate study currently being prepared. A first iteration of the framework for the role of mathematics was developed based on a collective walkthrough of a handful of the reviewed studies. This collectively generated framework was then evaluated as an analytical device via an individual reading of each of the 37 studies. We found that this framework effectively helped make sense of the role of mathematics in integrated STEM teaching and learning activities. The next step was to further develop, define and refine the elements of the framework (Kristensen & Seidelin, 2021). In the following section, a description of the framework is presented.

Results

The framework (see Figure 1) describes how mathematics interplays with the other STEM disciplines in STEM activities. The framework addresses the discussion highlighted in earlier research regarding the reciprocal relation between mathematics and the other STEM disciplines.

We identify two distinct but often simultaneously represented roles played by mathematics: (1) mathematics can be applied as a tool in STEM activities; and (2) mathematical objectives can be regarded as the primary purpose of STEM activities, i.e., mathematics is the aim. When mathematics is used as a tool, we identify different roles for mathematics. First, we find examples in which mathematics is used in combination with the other disciplines in problem-based courses—these are teaching activities where mathematics is used to pose, understand, and/or solve the problem. In the process of posing problems mathematics can e.g., be used to choose which problems are most important to investigate based on for example analysis of data. Schoenfeld (2016) describes the process of problem-solving in mathematics in six steps; understand/read the problem, analyze the problem, explore the problem, devise a plan, carry out the plan (implement the plan) and look back over the result (verify). In STEM activities the chosen problems are not purely mathematical and hence mathematics is applied to solve a problem from the real world through the process of mathematical modelling (Maass et al., 2019).

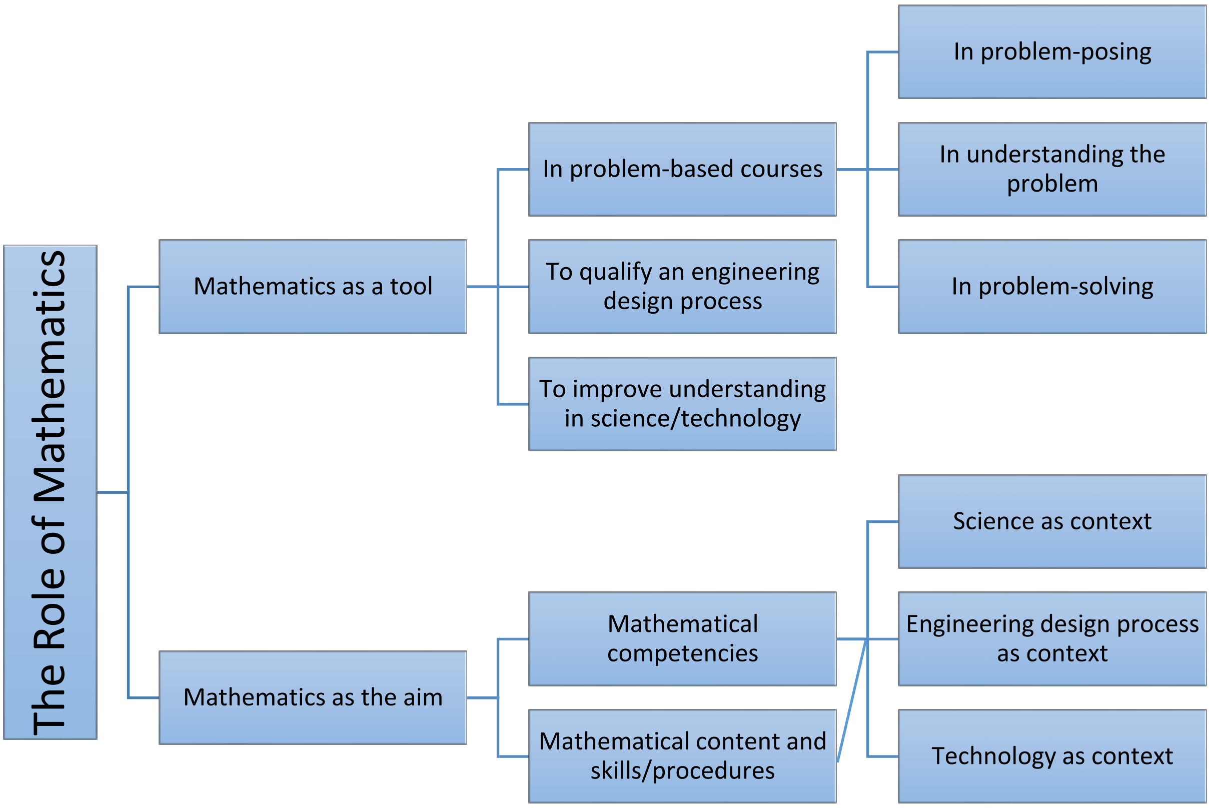

Figure 1. Proposed Framework for analysing the Role of Mathematics in Teaching Activities

Second, mathematics can be regarded as a tool underpinning the other disciplines, e.g., mathematics is used to qualify an engineering design process to enhance the process and the products. The engineering design process is a systematic way of working where a product should be optimized under given constraints (Moore et al., 2018). The process may consist of the phases identify, design, build and test solutions to a problem (Honey et al., 2014). Mathematics can here be applied in in all the phases for example by measuring, making calculation and analysing in the testing- phase (Auner et al., 2018). Third, mathematics is used to support the development of a deeper understanding of the science or technology being explored in the STEM activity.

In some STEM activities mathematics is the aim, and hence mastering mathematics is the primary purpose and it is mathematical objectives that are the primary objective of these activities. In these cases, we distinguish between two types of mathematical objectives: competencies (e.g., mathematics modelling competence or mathematical reasoning competence) and learning mathematical content and skills (e.g., understanding concepts like numbers, algebra, geometry). Competence describes the ability to act appropriately in a given situation (Larsen & Svabo, 2002). When we refer to mathematical competencies, we use the definition posited by Niss & Højgaard (2011), who distinguish between mathematical competence and mathematics skills, describing mathematical competency as 'a well-informed readiness to act appropriately in situations involving a certain type of mathematical challenge' (Niss & Højgaard, 2011, p. 49).

In the next section, we use two selected cases from the study sample to demonstrate how the proposed framework, can be used when describing and analysing STEM activities.

Case Study

Case 1: Mathematics as a Tool in an Engineering Design Process

The first case is described in a study by English and King (2018) titled STEM Integration in Sixth Grade: Designing and Constructing Paper Bridges (Study 9). It represents the category Mathematics as a tool in the presented framework. In this case there is a description of a STEM activity for sixth graders involving designing and constructing a paper bridge that can withstand an optimal load. The case was chosen because it provides an exemplary engineering activity in which mathematics is described very explicitly. The activity addresses the core objectives and themes of the teachers' existing curricula in mathematics, science and design technology. The overarching objective of the activity—for the students—is to participate in and understand an engineering design process to build the strongest possible bridge while drawing on their mathematical and scientific knowledge and skills. For mathematics, several objectives and content are explicitly included: apply estimation and measurement skills, apply spatial reasoning in recognising and working with different 2-D and 3-D shapes, communicate design details through 2-D and 3-D representations, and understand the basic notion of scale (Study 9, 2018, p. 869). The students use mathematical content in all steps of the engineering design process, e.g., using specific geometrical shapes, and recognising the importance of cost effectiveness when selecting the types and amount of materials to be used for the bridge, and mathematics can clearly be identified as a tool underpinning the engineering design process. Mathematics is thus not the overarching objective of this course. However, in this activity, we see a balance between all the disciplines; this activity is an example of an engineering design process where mathematics is included and not overshadowed by science.

Case 2: Mathematics used to Qualify Science Understanding and as Specific Aims

The second case is a study by Geiger (2019) titled Using mathematics as evidence supporting critical reasoning and enquiry in primary science classrooms (Study 14). The study includes a vignette about a teaching course that draws on observational data on a year 1 class and includes a post-lesson teacher interview. The content in this STEM activity is the growth rate of bean sprouts when exposed to different levels of sunlight while holding other variables constant (Study 14, p. 935). Each student was responsible for a bean sprout contained in a Ziplock bag with a piece of wet cotton wool. The bags were then subjected to different amounts of sunlight. The overarching aim of the activity is to develop students' critical capability and reasoning through mathematics based arguments (Study 14, p. 936).

This case was chosen because it highlights how the framework is not intended as a simple categorisation device, as the role of mathematics in this STEM activity can be recognised as both a tool to develop an understanding of science or as the aim for the teaching.

In describing the STEM activity, the teacher makes it clear that there are specific objectives that relate to the development of an understanding of specific mathematical knowledge: time, measurement, comparison (graphically and numerically), and variance. Moreover, the students expend considerable time developing the effective use of a ruler where the students previously only have made use of informal measurement techniques. Hence the students work with the concept of formal measurements, which is an important and integral part of mathematical curriculum in primary mathematics teaching (Lehrer 2003).

On the other hand, mathematics is also a tool for learning science. Without the skills of using a ruler and mathematical representation of the length of the bean sprout, it would be difficult for the students to develop a deep understanding of the effect of sunlight on the growth of the bean sprout.

The Role of Mathematics in the Selected Studies

In this section, we use the framework to identify tendencies relating to the role of mathematics in the 37 selected studies. First, it is a very apparent tendency that mathematics is predominantly used as a tool in STEM activities. Only in six cases (Study 2, Study 7, Study 14, Study 17, Study 23, Study 31) did we find that the overall purpose of the activity is to enhance the students' mathematical competencies, skills, and/or knowledge. However, in five of those cases (Study 7, Study 14, Study 17, Study 23, Study 31), it is difficult to determine whether mathematics is regarded as an objective or is a tool in the activity as in the second case described earlier. In these five cases, engineering (Study 31) and science (Study 7, Study 14, Study 23), and both engineering and science (Study 17) are used as the contexts for learning the mathematical objectives. However, mathematics can also be seen as a tool in an engineering design process or in understanding scientific content. In the last case (Study 2) in which mathematics is the overarching objective, it is clearly the acquisition of mathematical knowledge and skills that is the purpose of the activity, while technology is used as the context for learning this (Study 2).

In the activities in which mathematics is a tool, we found that mathematics was most often used in an engineering design process. However, only in three of these activities (Study 8, Study 9, Study 10) does mathematics play a central and explicit role, with a clear description of the mathematical content and objectives. Case 1 is one (Study 9), and the other two activities—presented in Study 8 and Study 10—are by the same authors and are part of the same research project. Hence, our review confirms that engineering design processes are not often oriented towards mathematics. Mathematics is also often used as a tool to acquire understanding in science, but in most of these activities, mathematics does not play as clear a role as in Case 2. Mathematics as a tool in problem-based activities was not often observed in the reviewed studies, but there is a single instance in which mathematics is employed in problem posing (Study 35), there is one instance where mathematics is employed in understanding the problem (Study 24) and two instances of problem-solving in which mathematics is employed as a tool (Study 21, Study 22).

Discussion and Conclusion

The increased focus on STEM creates new opportunities for enhancing the learning of the individual disciplines—while interlinking them—to unravel real-world issues and solve problems (Bybee, 2018). However, many researchers argue that there is a potential risk that mathematics may be overlooked in integrated STEM approaches. Hence, we found a debate in the research literature over what the role of mathematics currently is and what it should be in STEM. The inquiry presented in this study is a contribution to this discussion and our review confirms the concerns that mathematics is currently overlooked in STEM approaches. In most STEM activities mathematics is a tool and often plays a subordinate role, but as Case 1 illustrates, it is possible to include mathematics in a meaningful way as a tool in a STEM activity centred around an engineering design process if the mathematical content and goals are made explicit. The other interplay, as described in the framework, is to have mathematical aims as the primary purpose when designing STEM activities. Based on our review, and at variance with Fitzallen (2015), we argue that it may be beneficial to focus more on the interplay in which mathematical content and goals are the primary aim of the STEM activity and the other disciplines or real-world problems are used as the context to learn mathematics. The categorisation of specific STEM activities will always be up for debate. Specific activities may fit well in more than one category; however, the proposed framework is not merely a simple categorisation device in which an item fits in only one box. Rather, it is a sense-making device in which an item can fit into more than one category. Mol and Law (2002) provide a critique of classificatory systems enacting simple orders and present a strong argument for representations which try to enact in more complex ways and tolerate overlap, interference, and multiplicity. An example is the concept of mathematical modelling, which can be regarded both as a specific aim of the activity (i.e., developing students' mathematical modelling competency is the primary aim of the activity) and as a tool for enhancing scientific knowledge and understanding (mathematical modelling is used as a tool when describing a system). This is not a weakness of the framework; rather, we see it as an advantageous feature of the framework, with potential for clarifying the more nuanced aspects of mathematics in STEM activities.

Several critical angles can be included in this review that could potentially influence how the framework is constructed. One such aspect that clearly has an impact is keyword selection. If we had included other keywords, the results could potentially have been different. The inclusion criteria are another aspect with similar implications. Potentially, if there had been fewer or more inclusion criteria, the framework would have been different (e.g., if we had included STEM in informal learning environments). However, because the framework has been discussed in different contexts, from research contexts to several conferences (see e.g., Kristensen & Seidelin, 2021) to actual application in practice (e.g., workshops with teachers participating in the LabSTEM project), we believe that the framework has a high degree of reliability.

We recommend the use of the framework developed in this study as a discussion and reflection tool. The purpose of this framework is to highlight—and to nuance—all the potential ways mathematics can interplay in integrated STEM approaches. In particular, we propose that the framework be used when developing STEM activities to produce an explicit awareness of the different roles mathematics can play. It may be difficult to support learning mathematics in integrated contexts, but this can be achieved if mathematics receives explicit attention (Honey et al., 2014). The end goal of developing this framework is to contribute to and qualify the decisions that are made concerning mathematics in STEM activities; and to do this in a way that may inform educators in their daily teaching both as a planning tool and as an analysing and reflection tool. We argue that by providing this tool to teachers who plan STEM activities, they may become more aware of the various possibilities, making it possible for STEM activities to be more varied as well as balance the focus among the different disciplines to avoid mathematics being overlooked.

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Author Information

Mette Als Kristensen

https://orcid.org/0000-0003-4323-4678

University of Southern Denmark

Department of Mathematics and Computer Science

Campusvej 55, 5220 Odense S

Denmark

Contact e-mail: *mettealskristensen@hotmail.com*

Dorte Moeskær Larsen

https://orcid.org/0000-0003-0866-2239

University of Southern Denmark

Department of Mathematics and Computer Science

Campusvej 55, 5220 Odense S

Denmark

Lars Seidelin

https://orcid.org/0000-0002-0322-5112

University of Southern Denmark

Department of Mathematics and Computer Science

Campusvej 55, 5220 Odense S

Denmark

Connie Svabo

https://orcid.org/0000-0001-5653-9222

University of Southern Denmark

Department of Mathematics and Computer Science

Campusvej 55, 5220 Odense S

Denmark

Appendix. Study Sample

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