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Research article

Teachers' challenges in teaching integrated STEM: In the light of PCK as an analytical lens

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Abstract: In this article, we examine the challenges that teachers perceive when developing, planning and implementing integrated science, technology, engineering and mathematics (iSTEM) activities through collegial collaboration in elementary and lower secondary schools in Denmark. The aim was for teachers to collaborate across disciplines and to develop and implement iSTEM teaching activities. Throughout this process, all the teachers reported their challenges through process papers and surveys, while selected teachers provided additional insights through interviews. A thematic analysis identified five themes concerning the challenges of teaching iSTEM: subject matter confidence and student-centred approaches; collegial collaboration; specific challenges in integrating subjects across disciplines; planning and implementation; and challenges related to students. When comparing the challenges identified in the literature to those emerging from our data, many similar issues were found, alongside new perspectives that raise questions about previous assumptions regarding the challenges and constraints of teaching iSTEM. Notably, the teachers' feelings of competence, enacted Pedagogical Content Knowledge and personal Pedagogical Content Knowledge when teaching iSTEM appeared to be related more to the procedural and pedagogical processes involved in using student-centred approaches than to the subject-specific content of the disciplines being taught.

Keywords: iSTEM education; iSTEM challenges; interdisciplinarity; pedagogical content knowledge; professional development

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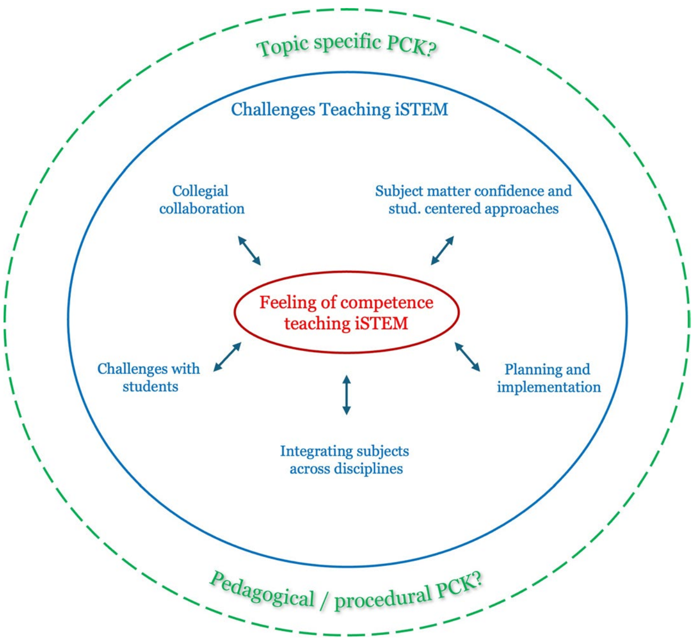

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1 Introduction

The idea of educating integrated science, technology, engineering and mathematics (iSTEM) teachers on how to enhance students' motivation and learning in these subjects has been discussed since the 1990s (Bybee, 2013). According to Kelly and Knowles (2016), only a few teachers in the US seem to know how to operationalise iSTEM education effectively. These findings also appear to be relevant in Denmark, particularly concerning primary and lower secondary school teachers (Larsen et al., 2022). Moore and Smith (2014) suggested that iSTEM should be viewed as a 'discipline' in its own right. Shaughnessy offered another holistic perspective, defining STEM education as solving problems that draw on concepts and procedures from mathematics and science while incorporating engineering design methodologies and utilising appropriate technology (2013, p. 324).

When discussing *STEM education*, it is evident that the term does not always refer to interdisciplinary teaching across the individual disciplines. Instead, it often addresses the disciplines individually. Consequently, we use the term interdisciplinary STEM teaching, abbreviated as iSTEM, in this paper and define it as 'teaching integrated science, technology, engineering and mathematics'. This interdisciplinary approach combines elements of these fields to foster connections between them and provides students with a holistic understanding.

In this paper, we define iSTEM education as occurring when two or more of the four STEM disciplines (science, technology, engineering and mathematics) are integrated in a relevant and meaningful way (Larsen et al., 2022). We refer to this as iSTEM and use the Pedagogical Content Knowledge (PCK) framework, specifically the refined consensus model (RCM) of PCK, as an analytical tool to examine teachers' ability to develop and teach iSTEM activities (Carlson & Daehler, 2019). While few studies have investigated the PCK required to teach iSTEM (Ling et al., 2020), scholars such as Srikoom et al. (2018) have identified four dimensions of effective teaching practice in this context, and An (2017) has examined interdisciplinary PCK. However, to our knowledge, no studies have utilised the recent RCM model of PCK as an analytical lens for discussing iSTEM teaching competence. In addition to presenting findings on the challenges teachers face when working with iSTEM, this paper seeks to address this gap.

As for iSTEM implementation, teachers must shift from teaching individual subjects to adopting an interdisciplinary approach across different STEM subjects. However, the Danish education system and teacher training programmes across all student levels primarily emphasise monodisciplinary teaching, with limited emphasis on interdisciplinarity (Uddannelses- og Forskningsministeriet, 2020). Specifically, there is no explicit requirement for Danish teachers to integrate subjects such as mathematics and science. To move iSTEM beyond a political agenda, it is crucial to understand and address the challenges that teachers perceive, particularly regarding their attitudes, beliefs and competencies.

Using the PCK framework, this study investigates the challenges that mathematics and science teachers encounter in the Danish LabSTEM project as they design and deliver iSTEM activities, thereby leading to the research question: **What challenges and constraints do teachers perceive when designing and implementing iSTEM activities in Danish primary and lower secondary schools?**

2 Teachers' iSTEM challenges in general – and through the PCK lens

2.1 Teachers' iSTEM challenges in general

In examining the challenges that teachers perceive in implementing iSTEM education, it becomes evident that these obstacles manifest in various forms across the literature. McDonald (2016) identified several hurdles that educators encountered when integrating student-centred approaches, such as inquiry or problem-based methods, into STEM education. These challenges include establishing collaborative learning environments, navigating uncertainty in outcomes and relinquishing control over students' progress. Thibaut et al. (2018) highlighted challenges related to teachers' attitudes toward teaching iSTEM, revealing that while participation in professional development courses like LabSTEM often fosters positive attitudes, years of experience teaching mathematics and total years of teaching unfortunately have a negative correlation with several aspects of teachers' attitudes toward iSTEM (Thibaut et al., 2018). This underscores the complex relationship between a teacher's attitude and their classroom practice when teaching iSTEM: Teachers with negative attitudes toward iSTEM tend to avoid learning how to teach it altogether (Appleton, 2003). Consequently, teachers must feel comfortable with the iSTEM subject being taught; otherwise, there is a tendency to either avoid teaching the subject or to present it superficially (Bursal & Paznokas, 2006).

Furthermore, disparities between teaching mathematics and science present significant challenges in STEM education. Wong and Dillon's (2019) investigation revealed a consensus among policymakers and educators regarding the notable absence of a link between science and mathematics instruction, stemming from these disciplines' asymmetrical interdependence, i.e., while science relies heavily on mathematics, the reverse dependency is not as pronounced. Moreover, science educators often fail to incorporate mathematics into their science teaching in a way that promotes holistic learning of both subjects. As a result, superficial integration becomes a pressing concern, particularly when mathematics is marginalised, as iSTEM is associated predominantly with science, often sidelining other disciplines' roles, including mathematics (English, 2016).

Another challenge is the limited emphasis on integration of subjects into teacher training. Kim and Bolger (2017) argued that many teachers feel ill-prepared for interdisciplinary curricula because their own education focussed primarily on monodisciplinary approaches. Structural challenges in primary school STEM education also have been noted (Venville et al., 2002), including the existing curriculum structure, large-scale assessment systems, school infrastructure – such as monodisciplinary classrooms like science labs and tech centres – and significant organisational demands placed on teachers. Moreover, there is a shortage of qualified iSTEM models and teaching courses, as Venville et al. (2002) found, leaving teachers forced to create their own iSTEM activities.

Each of these iSTEM-teaching challenges appears to reinforce the status quo, in which disciplines remain separate or are integrated in a more superficial manner. In this context, closely examining the prerequisites that teachers need to teach iSTEM is essential, particularly in terms of their knowledge and competencies.

2.2 Teachers' iSTEM challenges through the PCK research lens

It has been identified repeatedly and accepted widely that teachers' competencies and abilities as professionals in the classroom are two of the most important factors related to students' learning (Hattie, 2013; Van Driel et al., 2014). Shulman's (1986) frequently cited paper on teacher knowledge introduced PCK, describing it as a special amalgam of content and pedagogy that is uniquely the domain of teachers, i.e., their own special form of professional understanding (1986, p. 8). Today, one of the most important collective achievements in the field is the RCM of PCK, which identifies three realms or domains of PCK: collective PCK; personal PCK and enacted PCK (Carlson & Daehler, 2019). In this model, PCK is specified as both knowledge and skills, and enacted PCK can be understood as teaching-in-the-moment PCK (Alonzo et al., 2019). Personal PCK can be understood as each individual teacher's cumulative and dynamic PCK and skills, reflecting the teacher's own teaching and learning experiences, including what the teacher has gathered over the years from the contributions of others (e.g., colleagues, students, etc.). Collective PCK is a specialised knowledge base for science teaching that has been articulated and is shared among a group of professionals, related to teaching particular subject matter knowledge to particular students in a particular learning context. Enacted PCK is closely connected to and dependent on both personal PCK and collective PCK, as well as surrounding knowledge bases that are critical for actual teaching practice (Carlson & Daehler, 2019). As such, the ability to teach science and mathematics, and the confidence in doing so are related, from this perspective, not only to the discipline, but also to the content's topic specificity, which has been documented continually as being central to PCK for over a decade (Gess-Newsome, 2015; Loughran et al., 2004, 2012). This aspect is prevalent at the teacher education level as well, in which, for instance, subject-matter knowledge as a source of self-efficacy and a feeling of competence in teaching mathematics has been demonstrated to be central to pre-service teachers' perceptions (Bjerke & Solomon, 2020).

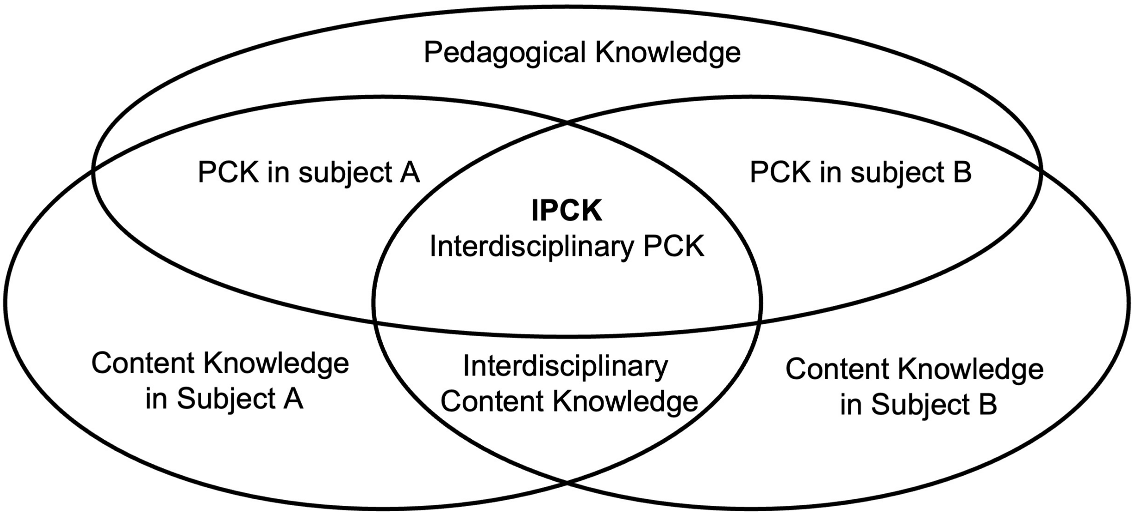
Collective PCK is specified in the RCM as a distinct realm. Through their research into collective PCK using content representation (CoRe) and pedagogical and professional-experience repertories (PaPeRs), Loughran and Berry, along with their various co-contributors, have demonstrated that teachers share aspects of PCK when teaching specific content to specific students at specific levels (Loughran et al., 2012; Loughran et al., 2004). In this regard, local collective PCK and professional contributions from trusted, skilled colleagues – referred to as significant colleagues – are described as central to PCK development (Ellebæk, 2021). Consequently, teachers' abilities to draw from this realm in actual teaching sequences are crucial.

Thus, a teacher's ability to teach a particular area, based on a solid knowledge base and individual teaching experience with specific content, is crucial. However, collective professional contributions and pedagogical reasoning in respective teaching areas are equally important (Park & Suh, 2019). In pedagogical reasoning around and in the actual moment of teaching (enacted PCK), the teacher draws from both personal and collective PCK and the surrounding knowledge bases.

When examining the connection between PCK and iSTEM, a larger Springer publication, *Pedagogical Content Knowledge in STEM* (Uzzo et al., 2018), and a recent review by Mientus et al. (2022) both highlight this connection as substantial. On one hand, PCK has been used to characterise STEM teachers' abilities, but on the other hand, the PCK focus has been more general, addressing STEM topics rather than iSTEM specifically. As mentioned earlier, the PCK required for facilitating integrated STEM may differ from the PCK needed for teaching science and mathematics topics separately. When investigating this connection, very few studies have focussed on the specific PCK needed to teach iSTEM. However, it seems evident that there is a lack of PCK among teachers in implementing iSTEM education as an approach to teaching and learning (Ling et al., 2020). A study by Aydin-Gunbatar et al. (2020) suggests that experienced teachers with solid, topic-specific PCK in certain subject areas can develop, to some extent, the ability to teach iSTEM disciplines in an integrated manner through a professional development project, but they were unable to achieve a balance among the involved STEM disciplines.

When discussing iSTEM teaching, it has been acknowledged widely that effective teaching is enhanced when teachers possess substantial content knowledge in specific subject areas (Nadelson et al., 2012). However, in the STEM education realm, the challenge lies in achieving integration across multiple STEM domains. An (2017) suggested that integrated PCK is founded on the interaction between two subjects, which he refers to as interdisciplinary PCK. As illustrated in Figure 1, An (2017) highlighted the complexity involved when two subjects are integrated. However, in iSTEM activities, multiple subjects may need to be integrated.

Figure 1. Interdisciplinary PCK



After An (2017)

Indeed, extant research has indicated that when teachers develop PCK, they are more likely to change their beliefs and practices in the classroom to engage their students in these learning environments effectively (Hall & Hord, 2006). This suggests that topic-specific enacted PCK, personal PCK and collective PCK are necessary within a certain interdisciplinary PCK area that spans at least two subject-matter areas.

The Magnusson model of PCK (Magnusson et al., 1999) has provided components that serve as valuable tools for examining the capacity to teach iSTEM. In a related study by Srikoom et al. (2018), four dimensions of effective teaching practice were identified as differentiating factors in a teacher's ability to teach iSTEM: the teacher's role and instructional approach; the iSTEM learning context; student engagement in the design process and the ability to connect with the content.

In this context, PCK previously has been used as an investigative tool concerning iSTEM teaching ability. However, new PCK theories, particularly the recent RCM model of PCK, to our knowledge, have not been described as an analytical lens for discussing iSTEM teaching ability. This literature gap and the absence of a specific analytical focus are areas that our present study aims to address and contribute to filling.

3 LabSTEM – the present study's context

The LabSTEM project (www.labstem.dk) is a research and development initiative spanning preschool, primary school, secondary school and vocational school. In this article, we focus on the participants teaching in primary and lower secondary schools only. Collaborating with various partners in the education sector, LabSTEM establishes dedicated laboratories in which primary and lower secondary teachers and researchers come together for workshops. On average, they attend approximately 8–10 workshops (depending on individual laboratories' preferences), including a combination of academic input and time allocated for planning their own activities. The teachers' goal was to create iSTEM activities for students. They then tested these activities in their own classrooms, sometimes with observations by some of their colleagues. Many of these activities have been published, enabling other teachers to use and benefit from them (Larsen et al., 2022). As an example of activities developed in LabSTEM for primary school, one activity involved students designing and constructing hedgehog shelters. Another activity, for lower secondary school students, engaged them in exercises related to a hydropower plant, culminating in the design and construction of their own mini hydropower plants. In both activities, students worked with integrated mathematics and science, i.e., science related to the hedgehog's habitat or the hydropower plant's functioning, and mathematics related to working drawings and the volume/angles of pipes. Both activities were based on engineering processes.

The LabSTEM project encourages teachers to follow five principles to develop a meaningful and effective pedagogical experience (Auning et al., 2023):

- Principle 1: iSTEM activities should help develop general education and action competence significantly.
- Principle 2: iSTEM activities should prioritise participant-centred approaches, such as problem-based or inquiry-based teaching approaches.
- Principle 3: iSTEM activities should focus on the real world and include real-world contexts.
- Principle 4: iSTEM activities should support learning objectives relevant to the curriculum at a particular level or stage of education.
- Principle 5: iSTEM activities should integrate two or more disciplines within STEM in a meaningful manner.

Approximately 200 educators participated in the LabSTEM project, tasked with developing and testing their own iSTEM activities. LabSTEM was active from 2020 to 2022, during which time, empirical data were collected, as detailed in the following section. After the LabSTEM project concluded, the initiative continued with some modifications under the LabSTEM+ project, which is ongoing from 2023 to 2025.

4 Methods

As noted earlier, the empirical data used in this study were gathered only from pedagogues and teachers working in primary and lower secondary schools. It is possible that trained pedagogues, rather than trained teachers, teach in primary school. They often come from after-school care programmes and participate in the teaching process. In the following section, we refer to them as 'teachers' or 'participants'.

An overview of the research project and analytical process is presented in Table 1 below:

Table 1. The timeline and four steps of the LabSTEM Project research process

LabSTEM Project Timeline (2020-2024)

The LabSTEM project employed a mixed-methods approach to investigate the challenges teachers face when implementing integrated STEM (iSTEM) activities.

Data collection and analysis were conducted in four steps:

Step 1: 2020-2022
LabSTEM Project

- **200 educators involved**
- **Each teacher participated in approximately 8-10 workshops**
- **77 teachers submitted process papers after each workshop, averaging three per teacher.**
- **102 teachers completed a survey after their participation in workshops.**

Step 2: Spring 2023
Data Analysis

- **Initial Analysis of Process Papers (N=77)**
- **Method: Inductive, data-driven coding based on participants' descriptions of challenges.**
- **Process: Thematic analysis (Braun & Clarke, 2006)**
- **Supplementary Analysis of Survey Data: Confirmation of the themes from the process papers. (N=102)**

Step 3: Fall 2023
Interviews

- **Semi-structured interviews with 7 teachers.**
- **Selection: Strategic selection to ensure maximum variation in experience, roles, and subject expertise.**
- **Purpose: To expand and elaborate on the themes that emerged from the process papers and survey data.**
- **Process: Full transcriptions of interviews, using a developed interview guide and transcription manual.**

Step 4: Spring 2024
Five Final Themes

- **Subject matter confidence and student-centered approaches**
- **Collegial collaboration**
- **Specific challenges in integrating subjects across disciplines**
- **Planning and implementation**
- **Challenges with students**

Step 1 in the table above refers to the part of the LabSTEM project in which the teachers were active in the gradual development and iterative implementation of iSTEM activities in their teaching. Steps 2–4 refer to the data analysis of process papers and surveys, the strategically selected interviews of seven teachers and the emerging five final themes. As such, the overall data comprised interviews (n = 7), process papers (n = 77) and survey responses (n = 102), all from teachers connected to primary and lower secondary schools in the LabSTEM project. The data were drawn from the same cohort of teachers, as all participants had taken part in the project. The teachers who completed the survey had an average of approximately 14 years of experience, with only five having less than five years of experience, indicating a relatively experienced group of teachers. The teachers were all either mathematics or science teachers, with approximately half being proficient in both disciplines.

The process papers originated from a series of LabSTEM workshops. After each workshop, the participants filled out a process paper comprising seven questions and additional background information, in which they reflected on areas such as processes and challenges. The questions included: 'What do you perceive as your primary challenge at the current stage of the process?' and 'What are you planning to implement in practice before our next meeting?' Overall, 77 primary and lower secondary teachers answered and submitted their responses, with each teacher averaging three process papers. The survey was to be completed by all participants at the end of their participation in the LabSTEM laboratory workshops. However, only 102 of the 200 LabSTEM participants completed the survey, possibly because some of the workshops were conducted online due to COVID-19. Nonetheless, all 200 participants were provided with a link to the survey, which comprised 32 items consisting of a combination of open-ended and closed-ended questions ranging from inquiries regarding number of years of teaching experience to the nature of their STEM activity, as well as more open questions regarding challenges they have encountered throughout the LabSTEM project.

The seven teacher interviews were semi-structured (Patton, 1990) and related to previously reported teacher challenges, as well as other experiences in their iSTEM activity. The interviewed teachers were selected strategically (Flyvbjerg, 2006), maintaining maximum variation (Patton, 1990) to identify key dimensions of variation among the teachers. This involved both experienced and inexperienced teachers, as well as teachers with different roles in the school regarding STEM education. The participants comprised mathematics and/or science teachers, as well as mathematics and science supervisors. All interviews were transcribed in full, and both an interview guide and transcription manual were developed to facilitate the process. Ethical considerations were observed throughout all parts of the research process, and informed consent was obtained from all research participants involved in the project (Cohen et al., 2011).

Methodologically, we began the analysis by identifying the challenges expressed by the teachers in the process papers (n = 77). The analytical procedure was inductive, with data-driven coding strongly linked to the data (Patton, 1990) and aspects of the challenges described by the participants. To complete this process, we followed the principles and the five phases for thematic analysis described by Braun and Clarke (2006). The initial phase involved immersing ourselves in the data to gain familiarity with its content (Phase 1). For example, during this stage, it was observed that many teachers referred to the challenge of insufficient time for planning, leading to the identification of ‘time’ as the primary theme. In subsequent phases (Phases 2 and 3), additional themes were generated and examined. Each member of the research group reviewed the dataset individually and proposed their suggestions for initial themes to the group. The following negotiation within the research group resulted in seven emerging themes:

1. Challenges in generating iSTEM teaching ideas
2. Challenges in teaching specific subjects (mathematics/science/engineering/technology)
3. Challenges in implementing activities
4. Challenges in collaborating with colleagues from other disciplines
5. Challenges in planning activities
6. Challenges related to students’ competencies
7. Challenges in teaching interdisciplinary approaches

During Phase 4, the themes were discussed and reviewed further to establish their relationships and definitions, while considering dual criteria-judging categories – internal and external heterogeneity (p. 91). It was observed that some themes exhibited significant overlap. Consequently, these themes were merged, resulting in the final identification, naming and definition of five themes (described in next section), which were used as starting points for analysis of the 102 survey responses. The surveys were collected before construction of the five themes, i.e., they were used primarily as a supplement to determine whether there was agreement in the very brief responses from the teachers regarding the five themes. Afterward, we conducted the teacher interviews (n = 7) to elaborate on the themes and gain more detailed and rich narratives of the specific challenges described in the process papers.

5 Findings: Teachers' challenges and constraints in the LabSTEM project

In this part of the article, we present the five themes that emerged from the data, with an emphasis on presenting the core findings in this section, while an analysis and discussion of the results will be presented in the next section: Analysis and Discussion.

The five developed themes are:

- Subject matter confidence and student-centred approaches
- Collegial collaboration
- Specific challenges in integrating subjects across disciplines
- Planning and implementation
- Challenges among students

The themes are described in detail in the following sections, in which we present only the findings. Shorter teacher quotes are taken from the process papers, while the narratives are derived from the interviews. The actual analysis of the specific findings will be an integral part of the discussion section.

5.1 Subject matter confidence and student-centred approaches

Many teachers reported experiencing challenges when teaching subjects in which they felt less confident and competent. Specifically, science and technology (S&T) teachers found it difficult to teach mathematics due to their limited knowledge and teaching experience in this field. Similarly, both mathematics and science teachers struggled with teaching technology and engineering, primarily because they lacked prior experience and subject-matter knowledge in these domains. Expressions such as, 'I only teach mathematics' or 'I only have some knowledge of science' were prevalent in several of the process papers and surveys. Altogether, 12 out of 77 teachers identified professional challenges related to their own limited subject-matter background, which they explicitly addressed in the process papers.

Examining this theme through the interviews revealed more nuanced challenges. In particular, experienced teachers – many of whom were educated more than 15 years ago and had no prior experience with inquiry-based methods – found it difficult to work with the student-centred approach in iSTEM. The apparently ‘loose’ structure of student-centred pedagogical approaches appears to challenge their strong sense of competence in their subject-matter knowledge and in teaching iSTEM. In this regard, many teachers perceived iSTEM teaching approaches as new ideas and challenges. Approximately one-third of the teachers who completed the survey expressed a need to see clear examples of iSTEM teaching sequences beforehand for inspiration.

However, two teachers with different educational backgrounds did not emphasise the same types of challenges when working with student-centred approaches. Science and technology teacher Jeppe, who was educated as a kindergarten teacher, had a clear understanding of hands-on and student-centred approaches, and he explicitly downplayed prior subject-matter knowledge’s importance. Both he and the students had to search for the necessary content knowledge during the teaching sequence, and this was communicated explicitly to the students to allow them to assume the roles of ‘investigative experts’. Jeppe’s approach was to give students the freedom to inquire, rather than being constrained by a monodisciplinary focus. As he said during the interview:

> *Perhaps it is an advantage that I do not have a traditional teacher education, where I have been schooled to teach a single subject…. I am much more focussed on the inquiry-based approach, where you set something up and say, ‘This is how the story is – this problem or this solution or this challenge we have to solve, and what can we do about that?’ And then, the thing about catching the children’s ideas and say, ‘Wau, I can see you have done this…’. In the LabSTEM project, I developed a scheme for myself and wrote down, ‘What is science, technology, engineering and mathematics in this area?’ and underneath, some focus words – words that will keep me focussed and I will use in front of the children. It has helped me a lot to focus the sequence because when you start with a narrative and then show the children many materials, then it’s good to have a tool to keep yourself grounded and focussed on what I exactly should be asking and what really is the focus of this sequence…. A focus word could be ‘calculation’ or ‘difference’ or something like that* (Respondent ‘Jeppe’).

Therefore, Jeppe attempted to support the various monodisciplinary terms’ content by employing subject-specific terminology, rather than considering the disciplines themselves in isolation.

Another teacher, Mette – who had a solid, but more interdisciplinary educational background – emphasised her professional identity as a moderator, rather than as an expert in a specific type of subject-matter teaching. She seemed to think that her most important competency was teaching interdisciplinarity, sometimes in subjects she may not feel competent in teaching separately. One challenge she perceived was that other, more traditionally educated colleagues did not meet this challenge with the same confidence:

> *Most teachers feel the need to control every aspect of their teaching in order to feel confident. However, when you engage in STEM education, with inquiry, engineering and technology processes, you cannot know it all. And I think it is difficult for many teachers because they have a kind of 'professional pride' in their teaching subjects, which I believe is valuable. But I also think that sometimes you have to take professional pride in the approach and pedagogical process behind your teaching, rather than focussing solely on your subject-matter knowledge. So, I have professional pride in knowing that my students will learn an incredible amount of knowledge through my teaching. I don't know exactly where we will end up, but I believe I will most likely challenge my students to achieve a suitable learning outcome* (Respondent 'Mette').

Mette describes above that she perceives her professional sense of competence as being primarily pedagogical and procedural, while most of her colleagues link their professional sense of competence to their subject-matter knowledge. Other interviewed teachers corroborated this observation. For instance, Lone expressed how teaching iSTEM was challenging and that it is much easier to be creative and confident in subjects in which one feels personally competent.

The reported challenges, particularly those related to incorporation of inquiry-based methods and adoption of student-centred pedagogy, highlight the obstacles that teachers perceive in transitioning to iSTEM pedagogical approaches. The hesitations that experienced teachers expressed, rooted in a traditional educational paradigm, underscore the need for targeted interventions to facilitate smooth iSTEM integration. The discrepancy in attitudes and approaches between teachers with diverse educational backgrounds, such as Jeppe and Mette, emphasises the complex nature of challenges that come with iSTEM implementation.

5.2 Collegial collaboration

Several teachers reported facing challenges related to collaborative collegiality. The lack of close and trusted colleagues within the respective LabSTEM teams seemed to pose a challenge when developing shared iSTEM activities. Many of the teachers expressed a sense of vulnerability when developing teaching sequences in a field in which they had no prior experience, particularly if they were the only teacher participating from their own school or team. Interdisciplinarity also was mentioned as a collaboration challenge: When teachers in different subject-matter areas must collaborate – such as when S&T teachers had to collaborate with mathematics teachers – they often had different approaches, methods and goals. This collaborative challenge was highlighted explicitly in the process papers and surveys by 17 out of 77 participants.

While examining this subtheme in the interviews, challenges related to collegial collaboration were evident, focussing on relationships between individual teachers within the respective groups. Few teachers were competent in all iSTEM subject-matter disciplines, so collaboration with colleagues seemed crucial. Teachers who worked in less-functional and -creative teams reported specific colleagues and their scepticism as clear reasons why their collaboration was less successful. Grethe, one of the teachers with much practical experience who was interviewed, viewed her contribution to the team as limited:

> *Personally, I always sit back in the chair, if I think there is the slightest bit of 'religion' in what I'm told to do.... I can tell from my management that we just have to participate in this STEM project.... But because it is so hyped, there is a form of religiosity attached to it.... And, at the same moment that it becomes like that, I'm going to sit and lean back a bit longer than I might need to. This expression about STEM is as a kind of 'hyped religion'* (Respondent 'Grethe').

Grethe's lack of enthusiasm and participation paint a picture of her contribution to the iSTEM activities as being limited. She felt pressure from her school's administrators, which led her to feel obligated to join the iSTEM project. Others on her team confirmed her lack of participation, and development of their iSTEM teaching activity was influenced only marginally by new ideas in STEM education. Grethe's reference to iSTEM as a 'religion' also may stem from teachers frequently being introduced to new projects and pedagogical approaches externally. This reflects 'project fatigue', a condition that can dampen engagement and stifle creativity, as demonstrated by Grethe's minimal iSTEM teaching contributions.

5.3 Specific challenges integrating subjects across disciplines

Several LabSTEM teachers reported challenges integrating subjects across different disciplines. They stated that it is difficult to learn and remember iSTEM to both understand and separate the four areas. Teachers from different subject-matter areas faced challenges in various ways with regard to the individual disciplines. For instance, one teacher explained that '[it is challenging for me to] get the "E" in iSTEM more involved in my course' or '[it is challenging for me to] make the "M" in iSTEM more visible/usable'. Both the survey responses and the process papers confirmed that integration of disciplines in STEM itself was perceived as a challenge, with 14 of 77 teachers explicitly problematising this issue.

When asked about integration of subjects during the interviews, the teachers described challenges related to specific subject-matter areas and the subject field itself. Content areas with which the teachers were not familiar appeared to challenge them through interdisciplinary teaching, particularly in relation to teaching subjects outside their area of expertise. The teachers also perceived substantial differences between integrating science and mathematics, particularly the perceived weak knowledge and perception of mathematics as a distinct field. Even the mathematics teachers themselves seemed to perceive mathematics primarily as a 'tool' for working in other disciplines, or a 'tool' for doing calculations. Both the mathematics and science teachers interviewed found mathematics to be a less-effective basis for creativity, indicating that mathematics, in most cases, appears to be the discipline added to the iSTEM formula after the other disciplines (S-T-E), which are the primary basis for creativity and development of the specific iSTEM teaching sequence. One of the interviewed S&T teachers, Nanna, was in a group of teachers who gave themselves the challenge that mathematics should be the basis for their iSTEM sequence because they saw a unique challenge here:

> *It was a bit difficult…. I have S&T on my backbone, and then I ask my colleagues, 'What is unique about mathematics?' … I am also a teacher in Danish, and I can easily tell you what is special about that specific teaching area. But for the mathematics teachers, it gets a little muddy…. In our group, they came up with something like 'patterns', and that this was unique for mathematics and that it was not present in other subject-matter disciplines. Um… They could say a lot of things – but then I could say, 'Well, we also have that in S&T…'* (Respondent 'Nanna').

Nana argued that when mathematics teachers themselves are unable to define what makes mathematics unique, it becomes challenging for others to integrate it into their teaching. Difficulties in making mathematics central to the integrative and creative parts of iSTEM teaching were present within many of the groups. Even when mathematics teachers were predominant in these groups, the difficulties persisted.

5.4 Planning and implementation

The actual planning and implementation of iSTEM activities were described as a challenge in the survey responses and process papers. The most frequently reported challenge was amount of preparation time. Many teachers indicated that additional time to prepare these interdisciplinary activities was necessary and that they unfortunately did not have enough time to dedicate to developing iSTEM sequences in the LabSTEM project. Even though these statements were related to the project, it seemed clear that integration of subjects itself was time-consuming in general.

Materiality also was mentioned as a challenge, with teachers reporting a lack of basic materials for hands-on activities, including access to various technologies. Teachers described this as a lack of necessary funding for materials, e.g., data loggers and '*that we always hit a wall when the funding limits good STEM ideas*'. Overall, 36 teachers out of 77 reported time, framing, planning or materiality as a challenge.

The aspects of missing funding and lack of time to plan were absent as themes in the interviews. The teachers seemed to be more interested in sharing their thoughts about other challenges than discussing and problematising these more generic aspects of teacher preparation.

5.5 Challenges with students

Students' engagement was described as a challenge in the survey responses and process papers. Several teachers highlighted that iSTEM teaching activities can be conducted only when students have a certain amount of subject-matter knowledge in advance. This theme was prominent in the survey responses and process papers, but only seven out of 77 teachers viewed this as a challenge that needed to be considered separately, and these challenges were nearly absent during the interviews.

Hanna mentioned challenges with students regarding the engineering parts of the sequence:

> *...something that I'm missing, and I think the students should have learned, is that 'engineering part', that 'testing, improving, testing, improving'. I thought it was missing in the students' work and they were not good at it.... I feel that they first have to learn this new way of working in a completely different way* (Respondent 'Hanna').

According to this quotation from Hanna, it is challenging for students to work in this different manner when engaging in engineering activities. She argued that students lack stamina and consistent on-task behaviour when working with the improvement part of engineering, and that they lack experience in the more student-centred approaches.

6 Analysis and discussion

When comparing the teaching challenges in iSTEM found in the literature with the challenges identified in our data, many similarities were found. However, when using RCM PCK terminology as an analytical lens, we also found new perspectives that emerged from our data, raising questions about our previous thinking related to the challenges and constraints in teaching iSTEM, as we discuss in this section.

Regarding Theme 5.1 above, the perceived lack of sufficient subject-matter competence and teaching background in iSTEM approaches was prominent in the teachers' quotes and narratives. The gap between teaching subject-matter areas, such as mathematics and science, seems to be a primary challenge. Statements like, 'I only do mathematics' or 'I only have some knowledge of science' reveal that the teachers lack a sense of competence in the other content areas. This seems to confirm extant research that has documented enacted PCK and personal PCK as being closely connected to the specific subjects taught and the particularity of teaching methods, teaching purpose and individual students (Gess Newsome, 2015, p. 36). Furthermore, the findings confirm the lack of a connection between science and mathematics teaching in general, as described by Wong and Dillon (2019), and that teachers tend to avoid teaching areas with which they are not comfortable (Bursal & Paznokas, 2006). Examining this aspect using PCK terminology, it seems to be a confirmation of personal PCK and enacted PCK, as well as teachers' confidence in teaching a certain content area in relation to their educational background in separate subject-matter areas and prior experience teaching near this content (Gess-Newsome, 2015; Loughran et al., 2004). For example, when a science teacher has no educational background and prior experience in teaching mathematics, her confidence, personal PCK and perception of enacted PCK in teaching certain mathematics content in general are – unsurprisingly – low.

The difficulties that teachers perceived when working with student-centred approaches, as reported by McDonald (2016), were present in our findings as well, in which the structure of inquiry or problem-oriented methods in iSTEM challenged the teachers' feelings of competence. In Hanna's narrative, she clearly perceived this as a challenge with her students in terms of getting them to work consistently and engage in engineering and student-centred approaches. As seen in other studies (e.g., McDonald, 2016, p. 541), Hanna revealed her discomfort with the uncertain aspects of her teaching sequence, and her perceived personal PCK in teaching iSTEM seemed low regarding this issue. The same might have been present in Jeppe's narrative as well, but he apparently has found a teaching approach in which inquiry seems to be more relevant to him than the specific subjects taught. In this regard, the strong enacted PCK and personal PCK that Jeppe perceived are related more to the teaching process around student-centred approaches than to the subjects themselves. As such, a quite surprising finding emerges, contributing new perspectives to the relationship between subject-matter knowledge and iSTEM pedagogical approaches, which unfold below.

The teachers also found interdisciplinarity and integration of the subjects themselves (S-T-E-M) to be challenging, as presented in Theme 5.3. Several of the interviewed teachers did not express positive attitudes towards interdisciplinarity, thereby confirming the lack of interdisciplinary PCK between two subject-matter areas, even if the teachers' personal PCK and perception of enacted PCK in teaching the respective subjects separately were prominent (An, 2017). In particular, the 'E' and 'M' in iSTEM seemed to represent challenges for many of the teachers. As English (2016) described it, mathematics' role seemed to challenge both science and mathematics teachers. In the narrative by the science and technology teacher Nanna, the mathematics teachers themselves had difficulties describing distinctive and creative aspects of mathematics, apart from viewing it solely as a tool for the science parts in the developed teaching sequences. Thus, superficial integration that diminishes the role of the disciplines themselves (English, 2016) was reported in multiple places in the data and was exemplified by Nanna's narrative concerning mathematics as a less unique field and a less creative point of departure for developing an integrative iSTEM sequence. Nanna presented a critical perspective on mathematics teachers' apparently low professional self-awareness. As such, she seemed to conclude that mathematics teachers' perception of collective professional knowledge around mathematics subject matter – and collective PCK of mathematics teachers – is weak in general.

Simultaneously, many of the teachers, according to the process papers and survey responses, felt less successful when failing to integrate all of the disciplines in STEM, even if this was not a specific agenda in the LabSTEM project itself. With this teacher expectation, interdisciplinary PCK, as described by An (2017), would become even more complicated when integrating all four disciplines. It seems reasonable to assert that the likelihood of finding a teacher with interdisciplinary PCK – as well as personal PCK – matching a developed activity with all the disciplines integrated would be quite low. This indicates a complexity and rarity regarding personal PCK in iSTEM, in which the teaching sequence's topic specificity could be challenged.

The collegial collaboration, as presented in Theme 5.2, between teachers with different subject-matter backgrounds was also a challenge. Teachers lacked trusted, skilled and close colleagues in their collaboration, described by Ellebæk (2021) as 'significant colleagues'. The differences reported by Wong and Dillon (2019) between mathematics and science teachers also were present in our data, particularly in the differences in pedagogy and methods, such as inquiry vs. more traditional pedagogical thinking. These differences seemed to characterise the divide between science and mathematics teachers, with iSTEM primarily associated with science (English, 2016). In this regard, a shared collective PCK, as reported elsewhere (Loughran et al., 2012; Loughran et al., 2004), was not present prominently in the iSTEM field despite the teachers having substantial separate teaching experience (personal PCK and enacted PCK) in the various iSTEM subjects involved.

Most interestingly, we found that the collaborating teachers' attitudes and beliefs were crucial in determining their engagement level with the project and their ability to involve students in the iSTEM learning environment (Hall & Hord, 2006). This is exemplified by Grethe, an experienced mathematics and science teacher who tends to 'sit back in the chair' if she perceives even the slightest hint of 'religion' in what she is asked to do. Thibaut et al. (2018, p. 987) reported a negative correlation between the number of years a mathematics teacher has taught and their attitude towards iSTEM. Grethe's experience aligns with this finding: Her lack of positive participation and collegial collaboration resulted in less-innovative teaching sequences, i.e., a reliance on previously completed lessons. Grethe's narrative highlights how teacher beliefs play a critical role in professional development and illustrates a general scepticism towards top-down interventions, such as political agendas influencing school practices, as discussed by Jones and Leagon (2014).

In this context, Grethe's resistance to developing shared collective PCK with colleagues in iSTEM teaching led her to label iSTEM as a kind of 'religion', fostering negative attitudes towards the approach. From an RCM PCK perspective, Grethe's resistance to developing collective PCK and engagement in the knowledge exchange – necessary for the development of personal PCK and enacted PCK – illustrates a gap in her professional growth (Carlson & Daehler, 2019). This resistance stems from her personal orientation and the barriers to external agendas she has set up, as often documented in PCK-related research (Magnusson et al., 1999; Gess Newsome, 2015; Carlson & Daehler, 2019). Furthermore, structural and organisational challenges – such as a lack of iSTEM teaching models, difficulties with testing and evaluation programmes, insufficient support from school management and limited time for collaboration – were identified frequently as obstacles in survey responses and process papers (Venville et al., 2002).

The challenges related to subject matter confidence and student-centred approaches may involve additional aspects, as mentioned above. Jeppe and Mette had significantly different perspectives on student-centred approaches, which they themselves explicitly connected to their multi/interdisciplinary-oriented educational backgrounds – Jeppe, as a kindergarten teacher, and Mette, as a teacher with a master's degree in an interdisciplinary field. Their narratives indirectly confirmed perspectives described by Kim and Bolger (2017) about the lack of interdisciplinary curricula in teacher education, which tends to have a very targeted, monodisciplinary focus. Indeed, Jeppe's hands-on and student-centred approaches to the iSTEM sequence, which he identified as his main teaching strength, allowed him to treat students as 'investigative experts'. This mindset led Jeppe to perceive himself as free from the limitations of a targeted, monodisciplinary focus, believing that such an approach could hinder students' ability to learn through investigation. Instead, he used a self-developed instrument with 'focus words' to keep the pedagogical process on track. Thus, his teacher-management system relied more on procedural and pedagogical processes than on specific subject-matter concepts. This view was echoed by Mette, who characterised her colleagues' professional identities as being tied closely to their subject-matter knowledge, calling it their 'professional pride'. However, she also suggested another form of professional pride, noting, 'I also think that sometimes you have to have professional pride in the approach and pedagogical process behind your teaching, rather than just your subject-matter knowledge'. Much like Jeppe, Mette's multi- and interdisciplinary background enabled her to focus more on her teaching approach and pedagogical thinking around student-centred approaches and interdisciplinarity in iSTEM. As noted earlier, she explicitly stated: 'I have professional pride in knowing that my students are going to learn an insane amount of stuff through my teaching'.

In examining this through the PCK terminology lens, the interviews with Jeppe and Mette revealed a contradiction and offered new insights into the research field. Despite their lack of a solid knowledge base and individual teaching experience in specific content areas that typically suggest limited interdisciplinary PCK, they displayed a strong personal

PCK and enacted PCK. This suggests that the perceived strength of their personal PCK and enacted PCK was tied to their procedural and pedagogical competence in teaching interdisciplinary and student-centred approaches, rather than their prior experience in specific content areas. Therefore, the topic specificity often highlighted in PCK-related research (Gess-Newsome, 2015; Loughran et al., 2004) may be less relevant in iSTEM teaching. The present study indicates that teachers like Jeppe and Mette perceive their personal PCK and enacted PCK regarding iSTEM teaching to be primarily procedural and pedagogical abilities centred around interdisciplinarity and student-centred approaches, particularly if the teachers have not been 'raised' from a highly focussed, monodisciplinary education (Kim & Bolger, 2017).

Considering the discussion above, RCM PCK terminology allows us to identify specific aspects — more precisely domains (realms) and professional knowledge bases — of teacher abilities in the development and teaching of iSTEM. As an analytical framework, RCM PCK terminology offers a new perspective on teachers' abilities to teach iSTEM, but it has limitations in that it does not provide terminology for examining the details within these domains. A more precise definition of domains in certain subject-matter areas or a combination of RCM with, for example, the internationally recognised PCK components suggested by Magnusson (1999) may provide a way to go 'a layer deeper' in future research.

7 Conclusion

The teachers' perception of a lack of sufficient teaching-background subject matter in certain areas of iSTEM was expressed prominently in their quotes and narratives. The gap between difficulties integrating content areas, such as mathematics and science, seemed to pose a significant challenge. The teachers' perceived difficulties with student-centred approaches also were prominent, with the seemingly 'loose' structure of inquiry or problem-oriented methods in iSTEM challenging both the students and teachers' feelings of competence. Teachers found the interdisciplinarity approach particularly challenging, particularly when it came to the 'E' (engineering) and 'M' (mathematics) aspects of iSTEM. In addition to these findings, collegial collaboration among teachers with different subject-matter backgrounds also proved to be a challenge, but challenges related to interdisciplinarity and student-centred approaches may involve additional aspects. Jeppe and Mette offered significantly different perspectives on student-centred approaches and subject-matter background than the other teachers, focussing more on procedural and pedagogical competence in interdisciplinary teaching and student-centred approaches, rather than on topic-specific teaching experience and personal subject-matter knowledge in any particular field.

Thus, the challenges that LabSTEM project teachers perceived align closely with those reported by other researchers in the field. This was expected, as it seems to be a natural consequence of the 'traditional STEM thinking' inherent in the LabSTEM project. Given the teachers' lack of educational background in certain fields, such as 'E' (engineering), one might even question whether it is reasonable to ask teachers to engage with content areas in which they have no formal training or preference. The teachers involved were challenged to develop iSTEM teaching sequences in groups, even though their varying subject-matter backgrounds represented most STEM disciplines. This highlights the connection between teacher ability and subject-matter educational background, which has been documented frequently in PCK-related research, in which collective PCK, enacted PCK and personal PCK often are demonstrated to be related to the subject's topic specificity. While there is no reason to question this well-documented finding in both STEM and PCK research, some findings in the present study suggest alternative conclusions and implications. Specifically, the teachers' PCK is perceived to be related more closely to procedural and pedagogical processes involved in interdisciplinary teaching and student-centred approaches. From this perspective, interdisciplinary PCK, as defined by An (2017), appears to be less central to personal PCK and enacted PCK in the iSTEM teaching context compared with the teacher's ability in the pedagogical and procedural processes. If teachers' feelings of competence, collective PCK, personal PCK and their teaching-in-the-moment enacted PCK in iSTEM are to be improved – and their reluctance to engage with iSTEM diminished — we suggest that focussing on procedural and pedagogical processes in interdisciplinary teaching and student-centred approaches is crucial. It might even be beneficial to discuss collective PCK, personal PCK and enacted PCK separately in these pedagogical processes, rather than primarily linking them to the topic specificity of the subjects involved in the iSTEM teaching sequence.

8 Implications

Based on our findings, if iSTEM is to succeed, changes in teacher education may be necessary. The current, pronounced, monodisciplinary focus should be challenged and complemented by a more interdisciplinary approach, enabling teacher students to build confidence in their ability to manage student-centred pedagogical approaches in iSTEM, rather than focussing solely on their lack of subject-matter competence in certain fields. In addition to the present study, we believe further research should track teachers with extensive experience teaching iSTEM to examine other in-depth aspects of their procedural and pedagogical experiences in this regard.

Research ethics

Author contributions

Ellebæk, J.J.: formal analysis; investigation; conceptualisation; methodology; validation; visualisation; writing (original draft preparation); review and editing
Larsen, D.M.: formal analysis; conceptualisation; validation; data curation; project administration; funding acquisition; formal analysis; writing; review and editing
Auning, C.: formal analysis; conceptualisation; validation; data curation; writing; review and editing

All authors have read and approved the published version of the manuscript.

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Data is unavailable due to privacy restrictions.

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The authors declare no conflicts of interest.

References

Alonzo, A. C., Berry, A., & Nilsson, P. (2019). Unpacking the complexity of science teachers' PCK in action: Enacted and personal PCK. In A. Hume, R. Cooper & A. Borowski (Eds.), *Repositioning pedagogical content knowledge in teachers' knowledge for teaching science* (pp. 271–286). Springer. https://doi.org/10.1007/978-981-13-5898-2_15

An, S. A. (2017). *Preservice teachers' knowledge of interdisciplinary pedagogy: The case of elementary mathematics-science integrated lessons, ZDM – Mathematic Education, 49*(2), 237–248. http://doi.org/10.1007/s11858-016-0821-9

Appleton, K. (2003). How do beginning primary school teachers cope with science? Toward an understanding of science teaching practice. *Journal for Research in Science Teaching, 33, 1–25*. http://doi.org/10.1023/A:1023666618800

Auning, C., Ellebæk, J. J., Bennedsen, K., Larsen, D. M., & Svabo, C. (2023). LabSTEM- STEM i grundskolen: aktiviteter og idéer. Syddansk Universitet. *Forskningscenter for Naturvidenskabelig Uddannelse og Formidling*. https://www.sdu.dk/Flexpaper/aspnet/Flex_document.aspx?doc=/sitecore/media%20library/Files/epage/Forskning/labstem/stem_i_grundskolenpdf?sc_database=web

Aydin-Gunbatar, S., Ekiz-Kiran, B., & Oztay, E. S. (2020). Pre-service chemistry teachers' pedagogical content knowledge for integrated STEM development with LESMeR model. *Chemistry Education Research and Practice, 21*(4), 1063–1082. https://doi.org/10.1039/D0RP00074D

Bjerke, A. H., & Solomon, Y. (2020). Developing self-efficacy in teaching mathematics: Pre-service teachers' perceptions of the role of subject knowledge. *Scandinavian Journal of Educational Research, 64(5),* 692–705. https://doi.org/10.1080/00313831.2019.1595720

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology, 3*(2), 77–101. http://doi.org/10.1191/1478088706qp063oa

Bursal, M., & Paznokas, L. (2006). Mathematics anxiety and pre-service elementary teachers' confidence to teach mathematics and science. *School Science and Mathematics, 106*(4), 173–179. http://doi.org/10.1111/j.1949-8594.2006.tb18073

Bybee, R. W. (2013). *The case for STEM education: Challenges and opportunities*. NSTA Press.

Børne og Undervisningsministeriet (2019). Fælles mål. https://www.uvm.dk/folkeskolen/fag-timetal-og-overgange/faelles-maal/om-faelles-maal

Carlson, J., & Daehler, K. R. (2019). The refined consensus model of pedagogical content knowledge in science education. In A. Hume, R. Cooper & A. Borowski (Eds.), *Repositioning pedagogical content knowledge in teachers' knowledge for teaching science* (pp. 77–92). Springer. https://doi.org/10.1007/978-981-13-5898-2_15

Cohen, L. Manion, L., & Morrison, K.. (2011). *Research methods in education*. Routledge.

Ellebæk, J. J. (2021). Primary science teachers' narratives about significant colleagues in light of collective PCK. *International Journal of Science Education, 43*(10), 1–18. http://doi.org/10.1080/09500693.2021.1927235

English, L. D. (2016). Advancing mathematics education research within a STEM environment. In K. Makar, S. Dole, J. Visnovska, M. Goos, A. Bennison & K. Fry (Eds.), *Research in mathematics education in Australasia 2012–2015* (pp. 353–371). Springer. https://doi.org/10.1007/978-981-10-1419-2_17

Flyvbjerg, B. (2006). Five misunderstandings about case-study research. *Qualitative Inquiry, 12*(2), 219–245. https://doi.org/10.18261/ISSN1504-2928-2004-02-

Gess-Newsome, J. (2015). A model of teacher professional knowledge and skill including PCK. In A. Berry, P. Friedrichsen & J. Loughra (Eds.), *Re-examining pedagogical content knowledge in science education* (pp. 28–42). Routledge. http://doi.org/10.4324/9781315735665

Hall, G. E., & Hord, S. M. (2006). *Implementing change: Patterns, principles and potholes*. Pearson/Allyn and Bacon.

Hattie, J. (2013). *Synlig læring-for lærere*. Dafolo.

Jones, M. G., & Leagon, M. (2014). Science teacher attitudes and beliefs: Reforming practice. In S. Abell, K. Appleton & D. Hanuscin (Eds), *Handbook of research on science education, Volume II* (pp. 844–861). Routledge. https://doi.org/10.4324/9780203824696

Kelly, T. R., & Knowles, J. G. (2016). A conceptual framework for integrated STEM education. *International Journal of STEM Education, 3*(11). https://doi.org/10.1186/s40594-016-0046-z.

Kim, D., & Bolger, M. (2017). Analysis of Korean elementary pre-service teachers' changing attitudes about integrated STEAM pedagogy through developing lesson plans. *International Journal of Science and Mathematics Education, 15*(4), 587–605. https://doi.org/10.1007/s10763-015-9709-3

Larsen, D. M., Kristensen, M. L., Hjort, M. F., & Seidelin, L. (2022). STEM-didaktik: Et internationalt, systemisk review om STEM-undervisningens didaktik. *MONA - Matematik- og Naturfagsdidaktik, 22(1)*. https://tidsskrift.dk/mona/article/view/131923

Ling, L. S., Pang, V., & Lajium, D. (2020). A case study of teachers' pedagogical content knowledge in the implementation of integrated STEM education. *Jurnal Pendidikan Sains Dan Matematik Malaysia, 10*(1), 49–64. https://doi.org/10.37134/jpsmm.vol10.1.6.2020

Loughran, J., Berry, A., & Mulhall, P. (2012). *Understanding and developing science teachers' pedagogical content knowledge*. Sense Publishers.

Loughran, J., Mulhall, P., & Berry, A. (2004). In search of pedagogical content knowledge in science: Developing ways of articulating and documenting professional practice. *Journal of Research in Science Teaching, 41*(4), 370–391. http://doi.org/10.1002/tea.20007

Magnusson, S., Krajcik, J., & Borko, H. (1999). Nature, sources and development of pedagogical content knowledge for science teaching. In J. Gess-Newsome & N. G. Lederman (Eds.), *Examining pedagogical content knowledge* (pp. 95–132). Springer. https://doi.org/10.1007/0-306-47217-1_4

McDonald, C. V. (2016). STEM Education: A review of the contribution of the disciplines of science, technology, engineering and mathematics. *Science Education International, 27*, 530–569.

Mientus, L., Hume, A., Wulff, P., Meiners, A., & Borowski, A. (2022). Modelling STEM teachers' pedagogical content knowledge in the framework of the refined consensus model: A systematic literature review. *Education Sciences, 12*(6), 385. https://doi.org/10.3390/educsci12060385

Moore, T. J., & Smith, K. A. (2014). Advancing the state of the art of STEM integration. *Journal of STEM Education: Innovations and Research, 15*(1), 5–10.

Nadelson, L. S., Seifert, A., Moll, A. J., & Coats, B. (2012). i-STEM summer institute: An integrated approach to teacher professional development in STEM. *Journal of STEM Education: Innovation and Outreach 13*(2), 69–83.

Park, S., & Suh, J. K. (2019). The PCK map approach to capturing the complexity of enacted PCK (enacted PCK) and pedagogical reasoning in science teaching. In A. Hume, R. Cooper & A. Borowski (Eds.), *Repositioning pedagogical content knowledge in teachers' knowledge for teaching science* (pp. 185–197). Springer. https://doi.org/10.1007/978-981-13-5898-2_15

Patton, M. Q. (1990). *Qualitative evaluation and research methods (2nd ed.)*. Sage.

Shaughnessy, M. (2013). Mathematics in a STEM context. *Mathematics Teaching in the Middle School, 18*(6), 324. https://doi.org/10.5951/mathteacmiddscho.18.6.0324

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching, *Educational Researcher, 5*(2), 4–14.

Srikoom, W., Faikhamta, C., & Hanuscin, D. (2018). Dimensions of effective STEM integrated teaching practice. *K-12 Stem Education, 4*(2), 313–330.

Thibaut, L., Knipprath, H., Dehaene, W., & Depaepe, F. (2018). The influence of teachers' attitudes and school context on instructional practices in integrated STEMeducation. *Teaching and Teacher Education, 71,* 190–205. https://doi.org/10.1016/j.tate.2017.12.014

Uddannelses- og Forskningsministeriet (2020). *Bekendtgørelse om uddannelsen til professionsbachelor som lærer i folkeskolen*. https://www.retsinformation.dk/eli/lta/2020/1140

Uzzo, S. M., Graves, S. B., Shay, E., Harford, M., & Thompson, R. (2018). *Pedagogical Content Knowledge in STEM: Research to Practice* (1st ed. 2018.). Springer International Publishing AG. https://doi.org/10.1007/978-3-319-97475-0

Van Driel, J. H., Berry, A., & Meirink, J. (2014). Research on science teacher knowledge. In N. Lederman & S. Abell (Eds.), *Handbook of research on science education 2* (pp. 862–884). Routledge. http://doi.org/10.4324/9780203097267

Venville, G. J., Wallace, J., Rennie, L. J., & Malone, J. A. (2002). Curriculum integration: Eroding the high ground of science as a school subject?. *Studies in Science Education, 37*(1), 43–83. https://doi.org/10.1080/03057260208560177

Wong, V., & Dillon, J. (2019). 'Voodoo maths', asymmetric dependency and maths blame: Why collaboration between school science and mathematics teachers is so rare. *International Journal of Science Education, 41(6)*, 782–802. https://doi.org/10.1080/09500693.2019.1579945