RESEARCH ON MATHEMATICAL COMPETENCIES IN ENGINEERING EDUCATION: WHERE ARE WE NOW?

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ABSTRACT

In tertiary mathematics education for engineers (hereafter called service mathematics education, SME), there is a long-lasting controversy on what and how to teach. The goal of SME is to provide a base for engineering-specific courses and to develop mathematical competencies needed for academic success and professional practice. A leading question in engineering education is how to take mathematical competencies into account when designing content. Mathematical competencies are employed to understand, judge, do, and use mathematics in a variety of mathematical contexts and situations in which mathematics could play a role [1]. Although mathematical competencies have been introduced for about two decades, Alpers [2] noted that research in engineering higher education had focused chiefly on the *modelling* competency and less on other competencies. By means of a scoping review, the current study aims to examine how mathematical competencies are investigated in higher education research. The main research question is “To what extent and in what ways have mathematical competencies been examined in higher engineering education research?” Papers were retrieved and qualitatively reviewed using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. A systematic search yielded 166 records, of which, 65 unique records were relevant to engineering education and screened for eligibility. A synthesis of 23 studies reviewed showed that *problem-solving* and *modelling* were the most investigated mathematical competencies and were often investigated together or with other mathematical competencies. The inconsistencies in the terminologies used suggest a need for clearer conceptualizations to advance research and inform practice on mathematical competencies.

1 INTRODUCTION

1.1 Service Mathematics in Higher Engineering Education

Mathematics is an essential discipline for many professions, and therefore, also in higher education [3]. In Science, Technology, Engineering and Mathematics (STEM) education this is even more the case since mathematics provides the basis and language for physics and engineering specific courses students need to complete. On the other side, mathematics is also viewed as a means to teach students to think analytically, to model and to solve problems in their fields [4]. Mathematics education for non-mathematics students (or major) is usually referred to as service mathematics education (SME), since the subject is being taught as a service to other disciplines and their programmes. The main challenge in this education is to tackle the question of what subjects to teach, in what depth, in how much detail, at what level, and with how much connection to applications. One way to deal with these challenges is to adapt the framework of mathematical competencies to the context of SME for engineers.

1.2 Mathematical Competencies

In 2000, the KOM (Competencies and the Learning of Mathematics) project was initiated in Denmark in response to various challenges in mathematics education at all levels. According to Niss [5], mathematical competence is defined as:

> “someone’s insightful readiness to act appropriately in response to all kinds of mathematical challenges pertaining to given situations.”

Eight mathematical competencies were identified that built the edifice to achieving mathematical competence. A mathematical competency is someone’s insightful readiness to act appropriately in response to a specific sort of mathematical challenge in given situations. These eight mathematical competencies are grouped into two categories. The first one consists of four competencies involving posing and answering questions in and through mathematics. The second category consists of four competencies involving handling the language, constructs and tools of mathematics (for an overview, see [1] and [5]). The level of competence is defined in terms of (1) degree of coverage: to what extent does an individual possess this competency; (2) radius of action: represents the range and variety of different contexts and situations in which the individual can successfully activate the competency; (3) technical level: level and degree of sophistication of the concepts, theories, and methods an individual can bring to bear when exercising the competency [5].

Deeken et al. [6] have shown the need for instructors to consider the problems first-year students encounter after transitioning from secondary school to university. For example, *mathematical representations* are used and presented differently in terminology, presentations, and mathematical evidence. In general, if the competencies are addressed in the curriculum, e.g., in Sweden [7], secondary education focuses on communicating the right solutions. However, university curricula focus on rigorous deductive argumentations and formal proofs requiring advanced *mathematical thinking* (one of the competencies). Consequently, new first-year students must adapt to a new academic learning environment concerning the learning of mathematical competencies in SME. Besides the challenges regarding the transition from secondary- to university education, mathematical competencies could potentially foster transfer from SME to engineering. As SME could support a characterisation of mathematics and mathematical competencies which address the variety of perspectives in different disciplines [4]. It would be of immense value to employ mathematical competencies at various educational levels, and especially in SME, to foster mastery and transfer of mathematics.

1.3 Current Study

Given the potential of mathematical competencies to guide the design and evaluation of SMEs, there is a need to better understand how mathematical competencies are being examined in higher engineering research. We first searched for review studies on mathematical competencies. However, we found that only a limited number of reviews have been conducted. This seems to suggest a gap in the field in synthesising research knowledge about how mathematical competencies have been employed. The current study attempts to fill this gap by performing a scoping review on how mathematical competencies have been studied in higher engineering education. Results of the scoping review will inform the field on the current state of mathematical competencies research in higher engineering education and provide insights into potential research directions.

2 METHODOLOGY

2.1 Identifying Research Question and Relevant Papers

According to Arksey and O'Malley [8], a scoping review typically consists of five steps: identifying research questions, identifying relevant studies, selecting studies, charting the data, and summarising the results. Our main research question is: "To what extent and in what ways have the eight mathematical competencies been examined in higher engineering education research?". Accordingly, the following sub research questions were formulated to guide the reviewing process:

- What is the current state of research on mathematical competencies?
- Which mathematical competencies were researched in the studies?
- How are mathematical competencies being employed in higher engineering education?

We first conducted searches across two databases (i.e., Scopus and Web of Science) to obtain relevant papers in February 2022. Each search string consisted of three categories of key words: 1) one mathematical competency (i.e., think*, reason*, model*, represent*, problem* solv*, handl* symbol* formal*), 2) a general term (i.e., math* competenc*) to limit the search to studies related to mathematical competence or competencies, and 3) educational level (i.e., higher education, tertiary, and universit*) to limit the search to studies conducted in higher education. We did not include two of the eight mathematical competencies (i.e., communicating in, with, and about mathematics, and making use of aids and tools) as they were relatively more difficult to assess [9]. In March 2022, two discipline-related journals, European Journal of Engineering Education and International Journal of Mathematical Education in Science and Technology, were searched using the same method. Along with a snowball search, 166 papers were identified in total.

2.2 Selecting Papers and Synthesising of Data

Results from the searches were uploaded to an intelligent systematic review software (rayyan.ai) that aided the selection and reviewing of the papers. We selected only papers that mentioned engineering by selecting the keyword “engineering”. After removing duplicates, 65 unique records were identified and screened by two independent researchers. 23 papers met the four main inclusion criteria and were included in the review: 1) relevant to SME, 2) mentioned mathematical competencies or mathematical competence, 3) were written in English, and 4) had full text retrieved. All selected papers were read in detail to extract information addressing the sub research questions.

3 RESULTS

3.1 Current State of Research on Mathematical Competencies

The 23 included papers consisted of journal articles (*n*= 12), conference papers (*n*= 10), and a book chapter (*n*= 1). The first paper was published in 2002, but the rest of the publishing activity was concentrated between 2011 and 2021 (see Figure 1). The reviewed studies were conducted in 14 different countries whereas the country was not specified in four papers. Figure 2 illustrates that most of the relevant research is in European countries. Regarding the type of tertiary education institution, universities were the most prominent (*n*= 15), followed by institutes (*n*= 3) and academies (*n*= 1). Five papers did not provide information about the type of institution. The information suggests a growing interest in mathematical competencies over the last decade at the tertiary level. While the main research activities are in European universities, there is also a developing interest across education institutions worldwide.

Research in the corpus was diverse, comprising empirical studies (*n*= 12), theoretical/conceptual papers (*n*= 5), reports on programme/instruction implementation (*n*= 4), and literature reviews (*n*= 2). Within the group of empirical papers, nine quantitative (*n*= 7 descriptive and *n*= 2 correlational) and three qualitative studies (*n*= 2 case studies and *n*= 1 narrative) were identified. Most papers focused on 1st year engineering students (*n*= 10), whereas several papers did not specify the students’ year level (*n*= 6). Out of the 23 papers, 13 provided information about the type of engineering programme. The studies were conducted in a diverse set of engineering programmes, including chemical and civil engineering. Of which, the highest number of studies were conducted in Electrical, Electronic, and Technology engineering (*n*= 10), and Mechanic and Materials engineering (*n*= 6).

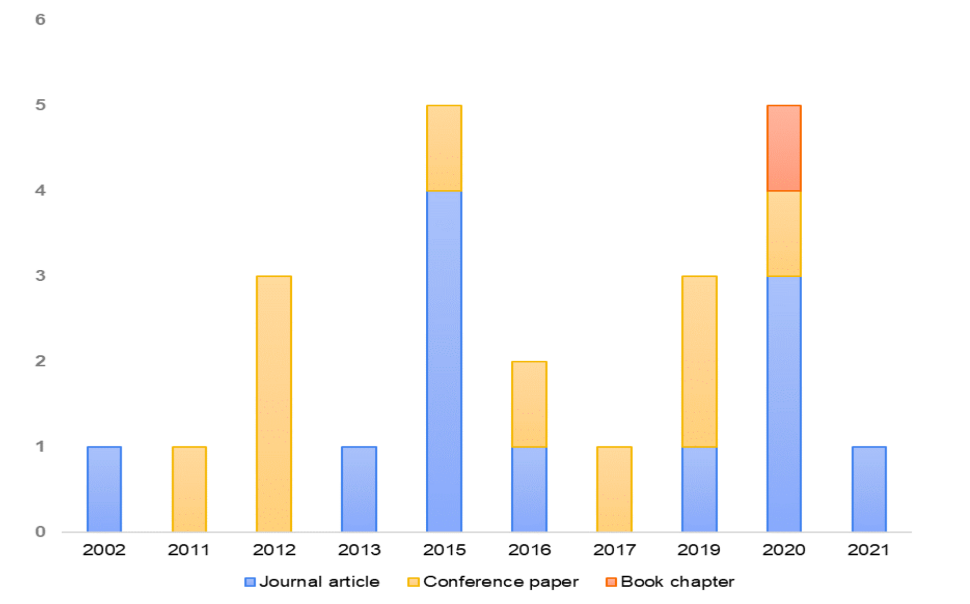

Fig. 1. Distribution of publication's number across the years

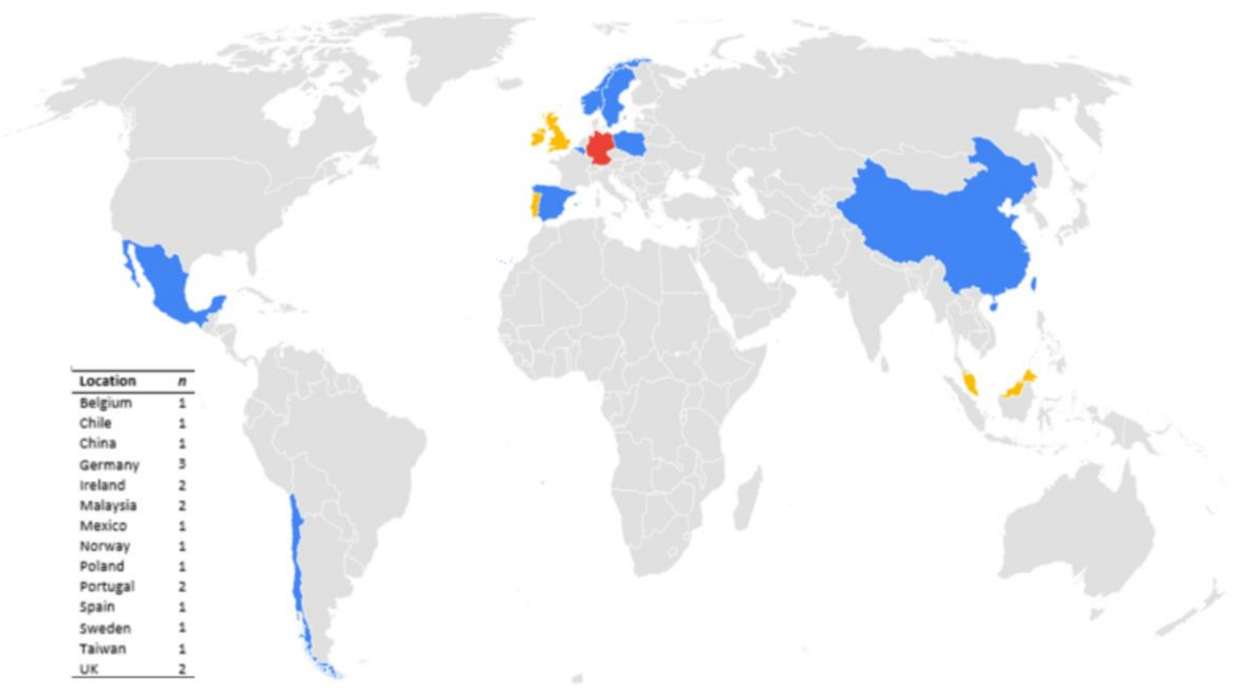

Fig. 2. Geographical locations of the reviewed papers

3.2 Mathematical Competencies Investigated in Engineering Education

A matrix table was used to map the terms employed to describe the concept of mathematical competencies and the specific mathematical competencies investigated in the papers. As shown in Table 2, two mathematical competencies, namely *posing* - and *solving problems* (C3) and *modelling* (C4), were the most investigated mathematical competencies. Not only were the two mathematical competencies individually investigated by the highest number of studies, but the two mathematical competencies were also frequently investigated together [10] and alongside other mathematical competencies [11]. There were no studies that explicitly investigated *representing math entities* (C5). Six studies (26%) investigated more than one mathematical competency (i.e., mixed). The investigation of more than one mathematical competency in a study suggests the interconnectedness of certain mathematical competencies.

Many studies did not use the term “mathematical competencies” when referring to a specific mathematical competency. For instance, *mathematical modelling* was referred to as skills [12] and competence [13]. Table 1 shows the diverse set of terms used in the studies. Our review showed that six studies (26%) mentioned the term “mathematical competencies” according to Niss’s [1] definition, while four studies used the term “mathematical competencies” but did not mention the framework by Niss. The term “competenc(ies)” was also often used with other terms, for example competence, skill, and literacy. Therefore, indicating a lack of consistency or clear definition for the terms used in mathematical competencies research.

Table 2. Mathematical competencies and terminologies used

	C2	C3	C4	all eight	mixed	general	Not specified	
competence		Kortemeyer & Biehler [14]	Hernandez-Martinez [13]		Othman et al. [25]: C1, C3 Quezada [26]: C1, C3	Nortvedt et al. [27]		5
competency (Niss)	Alpers [15]			Jaworski [16], [17] Pepin et al. [4]	Caridade &Rasteiro [9]: C7, C8		Carr et al. [29]	6
competency (Not Niss)		Reinhold et al. [21] Hussin et al. [22]	Huang [20]		Wedelin et al. [11]: C1, C3, C4			4
competence/ competency					Hennig [19]: C2, C4, C6			1
competency/ skill						Llobregat-Gómez et al. [28]	Carr et al. [30]	2
competency/ literacy						Lakoma, [18]		1
strategy					Gutierrez &Gallegos [10]: C3, C4			1
skills		de Laet [23]	Dan & Xie [12]					2
not specified			Lyon & Magana [24]					1
total	1	4	4	3	6	3	2	23
C1: Thinking, C2: Reasoning, C3: Posing and solving problems, C4: Modelling, C5: Representing, C6: Handling, C7: Communicating, C8: Making use of aids and tools								

3.3 Approaches in which Mathematical Competencies were Employed

For our third research question, we examined how mathematical competencies were investigated and organised the studies according to similar approaches. Table 3 provides an overview of the identified approaches to studying mathematical competencies. We first identified whether the mathematical competencies were investigated in a course context. Successively, we looked at teaching practices and student preparedness for math education.

The studies in the category of "in a course context" were further organised into three subcategories. The first subcategory consists of three studies investigating assessment and how an assessment tool measured a certain mathematical competency [14], [25], [26]. For example, in Kortemeyer & Biehler [14], student-expert-solutions were used as a tool to analyse students' *problem-solving* process. Another subcategory consists of studies exploring how tasks can be designed to develop mathematical competencies [15], [16], [17]. Alpers [15] provided examples of tasks to illustrate how *mathematical reasoning* can be used to set up a curriculum for a practice-oriented study course in mechanical engineering. Jaworski [16],[17] also provided a clear example of how an inquiry-based task helps develop the eight mathematical competencies.

The largest subcategory comprises studies that examine various teaching practices [9], [10], [11], [13], [18], [19], [20], [28]. The teaching practices were briefly described in Table 3. Several studies examined the use of technological tools to promote the teaching and development of mathematical competencies. Lakoma [18] highlighted the need to use technology to teach mathematics. Other studies examined the use of technology to assess or teach mathematical competencies (e.g., video lessons in Caridade & Rasteiro [9] and wiki in Hennig et al. [19]. There is also a strong focus on enhancing teaching practices for *mathematical modelling* [10], [11], [13], [20]. The teaching practices investigated in the studies provide insights into how mathematical competencies can be used to better develop courses and activities to enhance SME.

Among the seven studies in which mathematical competencies were not investigated in a course context, five studies examine students' preparedness for higher engineering education using "general" mathematical competency test in relation to basic math knowledge and skills. Two studies investigated the relationship between specific mathematical competencies and other thinking skills: 1) *mathematical modelling* and *creating thinking* [12] and 2) complex word *problem solvin*g and spatial, verbal, numerical, and general *reasoning* abilities [21]. The studies in this category suggest that examining students' level of preparedness or state of competence is an emerging area of research focus.

Table 3. Overview of approaches investigating "mathematical competencies"

Approaches	Paper and short description	Course name
In a course context		
Assessment	Kortemeyer & Biehler [14]: Student-expert-solutions in four exam exercises	Ordinary Differential Equations
	Quezada [26]: 10 open questions designed according to three types of mathematical competences	Calculus I
	Othman et al. [25]: Rasch Measurement Model to examine the reliability and fit of exam questions	Engineering Mathematics I-Vector Calculus
Task-related	Alpers [15]: Example tasks on how *mathematical reasoning* can be acquired	not in a specified engineering course
	Jaworski [16], [17]: Analysis of an inquiry-based task	not in a specified math course
Teaching practices	Caridade & Rasteiro [9]: A project involving students developing video lessons	Mathematical Analysis I
	Gutierrez & Gallegos [10]: Modify teaching of mathematics through *mathematical modelling* to promote critical thinking	Differential Equations
	Hennig [19]: Use of wiki in lectures and supervised exercises to provide short mathematical digressions	Fundamentals of Electrical Engineering
	Hernandez-Martinez [13]: Designed innovative aspects to teach *mathematical modelling*	not in a specified math course
	Huang [20]: *Mathematical modelling* activity and instruction using a transition framework	Calculus
	Lakoma [18]: Provided examples on how technology is useful for teaching mathematics, specifically in statistics	Statistics and Probability
	Llobregat-Gómez et al. [28]: An active methodology that requires students to design activities	Mathematics I
	Wedelin et al. [11]: A course with six modules and a small set of realistic problems	Modelling and problem solving
Not in a course context		
Specific competency test	Dan & Xie [12]: 22 Multiple-choice questions to test students' *mathematical modelling* from Lingefjärd [31]	
	Reinhold et al. [21]: Complex word *problem solving* ability was measured with items from published PISA mathematics items.	
General test	Carr et al. [29], [30]: Diagnostic test	
	de Laet [23]: Mandatory positioning test for aspiring engineering students	
	Hussin et al. [22]: Test of mathematics knowledge and competency for students entering University Teknikal Malaysia Melaka (UTeM)	
	Nortvedt et al. [27]: Test of basic 'mathematical knowledge'	
Reviews		
	Lyon & Magana [24]: Systematic review of 27 journal articles on *mathematical modelling* in engineering education	
	Pepin et al. [4]: Literature review of 140 papers, book chapters, and proceedings to examine innovative teaching and learning practices in mathematics in engineering education	

4 DISCUSSION AND CONCLUSION

The objective of the review is to examine how mathematical competencies are being investigated in higher engineering education where mathematics is typically taught as a service subject. Addressing Research Question 1, this scoping review yielded 23 papers with studies conducted across 14 countries employing a diverse set of methodological approaches. The results are aligned with Niss et al.'s [32] finding on the conceptualization of competencies in mathematics education research. When naming mathematical mastery, the terminologies used are highly diverse. Without a deeper analysis, it is not clear whether the different terms refer to the same concept nor whether the same term was used but are referring to different constructs.

Despite the presence of terminological issues, the studies in this review suggest a shift towards symmetry in adopting the definitions provided by Niss [1]. A common definition would help to advance research and inform practice on mathematical competencies. Educators and researchers can build on each other's work by employing a similar definition and use the eight mathematical competencies from Niss as a starting point. Another way to move forward is to empower math educators in embracing and owning the notions of mathematical competencies [32]. By doing so, educators can better develop teaching materials and approaches to foster mathematical competencies.

For Research Question 2, this review found that research has focused on the investigation of two specific mathematical competencies, *modelling* and *problem solving*, either independently or combined in the same research context. An explanation could be that these two competencies play a central role in the education of future engineers [33]. However, this finding suggests the need for future research to examine how other mathematical competencies can be individually supported within service-mathematics courses for engineering students.

Furthermore, the analysis indicates that studies often investigate a combination of three or more individual mathematical competencies either as independent or interdependent concepts, e.g., [10]. This observation might be related to the fact that teaching methods and learning materials rarely address isolated mathematical competencies in authentic educational settings. In this case, Niss et al.'s [32] recommendation for more empirical research on the interconnectedness among individual competencies is highly relevant.

In relation to Research Question 3, the studies reviewed show an emerging interest in the abovementioned connection in the level of task analysis, e.g., [17]. Future research could investigate the relevance of different competency combinations at the level of various service-mathematics courses or engineering programmes, e.g., [15] and [16]. Moreover, Lakoma [18] and Pedersen et al. [34] suggest that there is a need to examine how development of mathematical competencies can be supported by various technologies given that digital technologies are becoming a commonplace at school and at work. An example of course design, using mathematical competencies linked to digital technologies and workplace contexts is the concept of Techno-mathematical Literacies by Van der Wal et al. [35].

The current scoping review had some limitations. First, only two major databases were used, so the search was not exhaustive. To gain a more in-depth understanding of mathematical competencies research in higher engineering education, a more systematic review of studies will be much needed. Nonetheless, the current scoping review acts as a precursor for future systematic review and raises potential questions and areas for research.

Secondly, the scoping review did not look at the dimensions for specifying and measuring progress in mathematical competencies. Future reviews could consider examining dimensions for a more thorough investigation of the literature on mathematical competencies. The goal of defining and researching mathematical competencies in SME is to support course and curriculum design based on competencies. This review shows that the field is not at that point yet with substantial research findings to guide the design of SME.

As an extension to the current scoping review, our future work will include investigating lecturers' perspectives on developing mathematical competencies in service mathematics courses. To conclude, the scoping review provides a contemporary understanding of the trend of mathematical competencies research in SME and adds to the emerging research field of competence-based course and curriculum design by identifying the gaps in research between the definition of competencies, their interconnectedness, and their assessment.

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