European Commission

STEM competencies, challenges, and measurements: a literature review

Author:
Pokropek, A.

Editors:
Mazzeo Ortolani, G.
Karpinksi, Z.
Biagi, F.

2024



Joint Research Centre

This publication is an External Study report prepared for the Joint Research Centre (JRC), the European Commission's science and knowledge service. It aims to provide evidence-based scientific support to the European policymaking process. The contents of this publication do not necessarily reflect the position or opinion of the European Commission. Neither the European Commission nor any person acting on behalf of the Commission is responsible for the use that might be made of this publication. For information on the methodology and quality underlying the data used in this publication for which the source is neither Eurostat nor other Commission services, users should contact the referenced source. The designations employed and the presentation of material on the maps do not imply the expression of any opinion whatsoever on the part of the European Union concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

Contact information
Name: Giovanna MAZZEO ORTOLANI
Address: Rue du Champ de Mars 21, 1050 Brussels, Belgium
Email: Giovanna.MAZZEO-ORTOLANI@ec.europa.eu
Tel: +32 229 83233

EU Science Hub
https://joint-research-centre.ec.europa.eu

JRC138618

PDF ISBN 978-92-68-20938-7 doi:10.2760/9390011 KJ-01-24-060-EN-N

Luxembourg: Publications Office of the European Union, 2024

© European Union, 2024



The reuse policy of the European Commission documents is implemented by the Commission Decision 2011/833/EU of 12 December 2011 on the reuse of Commission documents (OJ L 330, 14.12.2011, p. 39). Unless otherwise noted, the reuse of this document is authorised under the Creative Commons Attribution 4.0 International (CC BY 4.0) licence (https://creativecommons.org/licenses/by/4.0/). This means that reuse is allowed provided appropriate credit is given and any changes are indicated.

For any use or reproduction of photos or other material that is not owned by the European Union permission must be sought directly from the copyright holders.

How to cite this report: European Commission, Joint Research Centre, Pokropek, A., *STEM competences, challenges, and measurements: a literature review,* Editors: Mazzeo-Ortolani, G., Karpinski, Z., Biagi, F., Publications Office of the European Union, Luxembourg, 2024, https://data.europa.eu/doi/10.2760/9390011, JRC138618.

Table of Contents

Abstract 3

Acknowledgements 4

Executive summary 5

1 Introduction 7

2 Traditional STEM education 8

3 Integrated STEM education 11

4 Arts and STEAM education 13

5 STEM education outcomes: literacy, competencies, knowledge, skills, and attitudes 15

6 Navigating today's landscape of STEM education: a summary attempt 18

7 What does research tell us about STEM and STEAM education and outcomes? 20

8 What does research tell us about STEM education and outcomes in EU27? 22

9 Challenges of STEM education 25

9.1 Define the specific outcomes that we aim to measure 26

9.2 Develop or adapt tools for measuring these defined outcomes 26

9.3 Identify which educational practices and programs are effective 26

9.4 Evaluate the feasibility of implementing educational practices and programs 27

9.5 Improving students' and citizens' engagement, participation, and accomplishments in STEM disciplines 28

9.6 Providing students and citizens more opportunities to engage with competent and influential STEM educators and leaders 28

9.7 Tackling and narrowing the disparities in STEM talent and skills 29

9.8 Raising community consciousness and encouraging backing for STEM projects 29

10 Resources that can help analyse STEM outcomes in Europe 30

10.1 Programme for International Student Assessment (PISA) 30

10.1.1 PISA Student Questionnaire 32

10.1.2 PISA School Questionnaires 33
10.1.3 PISA Parent Questionnaire 34
10.1.4 PISA ICT Familiarity Questionnaire 35
10.2 Trends in International Mathematics and Science Study (TIMSS) 36
10.2.1 TIMSS Student Questionnaire 38
10.2.2 TIMSS Teacher Questionnaire 39
10.2.3 TIMSS School Questionnaire 40
10.2.4 Other TIMSS Questionnaires 40
10.3 Programme for the International Assessment of Adult Competencies (PIAAC) 42
10.4 International Computer and Information Literacy Study (ICILS) 43
Conclusions 46
References 49
List of abbreviations and definitions 55
List of figures 56
List of tables 57

Abstract

STEM education, encompassing science, technology, engineering, and mathematics, has evolved significantly due to technological and societal shifts. Integrated STEM and STEAM (adding arts) approaches are becoming more spoken, focusing on developing 21st-century skills like creativity and problem-solving. Although, from a broad perspective, integrated STE(A)M approaches are appealing and theoretically sound, their inconsistent definitions and operationalizations complicate curriculum design, evaluation, and scientific studies. The scarcity of research on STEM education, particularly in the European context, underscores the urgent need for more evidence-based practices. While international large-scale assessments could provide cross-country insights into STEM education, more well-designed studies are needed to understand the effectiveness of STEM and STEAM education, particularly in the European context. Promoting STEM research and securing adequate funding sources for such studies is essential to gaining a deeper understanding of STEM education and guiding its development based on more robust empirical foundations. Ultimately, such efforts will help shape a more effective and inclusive STEM education system responsive to the evolving demands of the modern workforce and society.

Acknowledgements

We would like to thank for the comments and feedback received from Maria Podlasek-Ziegler and Hugo Miguel Pinto de Abreu from the European Commission, Directorate-General for Education, Youth, Sport and Culture (DG EAC), and Anna Horvath from the European Education and Culture Executive Agency (EACEA).

Author

Artur POKROPEK (Polish Academy of Sciences, Institute of Philosophy and Sociology)

Editors

Giovanna MAZZEO ORTOLANI (European Commission, Joint Research Centre, Brussels)

Zbigniew KARPINSKI (European Commission, Joint Research Centre, Seville)

Federico BIAGI (European Commission, Joint Research Centre, Ispra)

Executive summary

Policy context

The rapid evolution of technology, alongside the green and digital transitions, makes the education of citizens in technical subjects — commonly referred to as STEM — an increasingly important issue. STEM education is crucial for the economies of EU countries and the broader well-being of citizens navigating an increasingly technical environment. The 2018 recommendation by the Council of the European Union on key competencies highlights the importance of STEM education. However, this concept is surrounded by many controversies, from the definition of STEM to practical questions about which educational approaches are most effective. The report provides a comprehensive overview of the history of the STEM education concept, its various interpretations, and current research status on STEM education, offering directions for evidence-based research in this field.

Key conclusions

There is no doubt among the majority of researchers and policymakers that STEM education is a critical area that needs to be developed. There are also key elements of policy actions that appear essential to ensure citizens acquire the appropriate STEM skills. They might be simplified into four broad directions:

- Increase student interest, participation, and achievement in STEM;
- Expand student access to effective STEM teachers and leaders;
- Reduce STEM talent and skills gaps;
- Build community awareness and support for STEM.

Although the overall picture is clear, important implementation details are still missing. Scientific and political discourse about the STEM education concept is not unified, and different concepts of STEM education exist in parallel with different ideas about best educational practices. One of the most important factors for developing STEM education is increasing the number of well-designed studies on the effectiveness of STEM and STEAM, particularly in the European context, where there is a significant lack of such research. New studies incorporating experimental and longitudinal designs could contribute to a better understanding of STEAM education. There is an increased need for research or applied programmes providing practical knowledge about STEM education and allowing evidence-based policymaking decisions. Such programmes should include the following components:

- Define the specific outcomes that we aim to measure;
- Develop or adapt tools for measuring defined outcomes;
- Identify which educational practices and programs are effective;
- Evaluate the feasibility of implementing educational practices and programs.

Main findings

The scarcity of research on STEM education, particularly in the European context, underscores the urgent need for more evidence-based practices. About 75% of STEM education research originates from the USA, with a significant lack of evidence from the European Union (EU). Furthermore, nearly

half of the publications are not research articles but discussions or summaries that do not significantly contribute to scientific knowledge in this field. This imbalance accentuates the relevance of more European-focused research in STEM education.

Large-scale assessments are the primary data sources for evaluating national and European educational outcomes. These assessments, like PISA and TIMSS, focus on elements of STEM, such as mathematics and general science skills, but largely exclude engineering, technology, and transversal skills. For science and mathematics, representative studies exist for school populations (PISA, TIMSS) and adults (PIAAC).

In the EU, many students fail to meet basic achievement levels, surpassing the 15% target for low achievers. TIMSS 2019 revealed that over 15% of students in grade 4 mathematics and science underperformed, with Latvia, the Netherlands, Ireland, and Austria showing the lowest rates. In secondary education, only a few educational systems met the target for low achievers in mathematics. PISA 2022 showed that around 30% of EU students underperform in mathematics (with nearly 50% from disadvantaged backgrounds), and 25% in science. Most EU countries have shifted towards discipline-specific science education in secondary education, moving away from the integrated STEM approach. While a substantial part of pedagogical literature advocates integrated STEAM education, its long-term impact remains to be determined. Several European countries have implemented national strategies and initiatives to enhance student engagement in STEM subjects. Germany, Italy, Austria, Slovenia, and Finland programmes focus on improving teaching standards and pedagogical approaches. At the same time, extracurricular STEM activities enrich learning in other countries like Czechia, Spain, Portugal, and Croatia.

Related JRC work

This project is part of a broader research agenda of JRC unit B.6, which analyses education, employment, technology transfer, and industrial strategy developments in the EU. Findings from this report may contribute to discussions on how to better prepare individuals and educational systems for the future, address skills shortages in STEM fields, and stimulate European competitiveness (Letta, 2024; Draghi, 2024).

Quick guide

STEM (Science, Technology, Engineering, Mathematics) and its extension STEAM (adding Arts disciplines) emphasize interdisciplinary learning to prepare students for a rapidly evolving world. STEM education focuses on technical skills, while STEAM emphasises creativity and critical thinking through the Arts. Both aim to develop 21st-century skills like problem-solving, adaptability, and innovation. Challenges include unclear definitions, lack of empirical evidence on effectiveness, and varying educational approaches. Current studies are often limited. Large-scale assessments like PISA and TIMSS provide the most comprehensive data; however, they have substantial limitations. Further research is needed to understand these models' long-term impact.

1 Introduction

The historical context of STEM (Science, Technology, Engineering, and Mathematics) education can be traced back to the launch of Sputnik in 1957 by the Soviet Union, a pivotal moment in the space race that highlighted the need for technological superiority and innovation (Gonzalez & Kuenzi, 2012; Sanders, 2009). This event catalysed a shift in educational priorities worldwide, emphasising the importance of science, technology, engineering, and mathematics to maintain or achieve global scientific leadership. The urgency of the Sputnik era laid the groundwork for the formulation, rapid development, and ongoing evolution of STEM as a critical educational focus.

As we advance through the 21st century, the rapid evolution of technology, notably artificial intelligence, alongside the green and digital transitions, is further reshaping the conceptualisation of STEM, expanding it beyond its traditional boundaries, emphasising the integration of its components and incorporating additional elements, such as arts (Mejias et al., 2021), thus evolving into STEAM (Science, Technology, Engineering, Arts, and Mathematics). This inclusion underscores the significance of creativity and innovation and highlights the necessity of imbuing education with 21st-century skills (21CS), such as critical thinking, problem-solving, and digital literacy (Kennedy & Sundberg, 2020; Holbrook et al., 2020).

The evolving nature of STEM competencies and the expansion of STEM to include STEAM further sharpens educational challenges. As the educational landscape shifts to embrace a more integrated approach to learning, the capacity to offer clear guidelines for teachers on how to teach STEM subjects most effectively becomes limited (Aguilera & Ortiz-Revilla, 2021). Similarly, for policymakers, designing educational environments and programs that are both effective and responsive to the demands of a rapidly changing technological and economic landscape becomes increasingly challenging (Kelley et al., 2016; Kennedy et al., 2014).

The difficulty in defining and measuring STEM competencies impacts educational outcomes and has broader implications for students' workforce readiness. As the global economy continues to evolve, driven by technological innovation and the integration of digital skills, the necessity for a workforce proficient in STEM disciplines becomes more critical than ever. However, more clarity and consensus on what constitutes essential STEM competencies is needed to ensure efforts to prepare students effectively for these future challenges (Bybee, 2013; National Research Council, 2011).

2 Traditional STEM education

The traditional notion of STEM education, encompassing the disciplines of science, technology, engineering, and mathematics, originates from a pragmatic response to emerging workforce needs. Initially, the term “SMET” was proposed by the National Science Foundation (NSF) in the United States during the 1990s to integrate these disciplines. However, to avoid the phonetic resemblance to “smut”, the acronym was rearranged to “STEM”, which has since become popular (Sanders, 2009; Rimes & León de la Barra, 2014).

The concept of STEM seemed to be an intuitive response to the evolving needs of a burgeoning economy. The seamless integration of science, technology, engineering, and mathematics offered a logical coherence, directly aligning with the skill sets required for economic development and innovation. This supposed inherent compatibility suggested that an educational focus on these areas could significantly contribute to a nation's technological advancement and competitive edge in the global market (Freeman et al., 2019).

To understand what STEM means in education, let us take a closer look and break down the core elements this acronym represents. Science is the systematic study of the natural world through observation and experimentation, aiming to uncover the laws governing the universe. It is the foundation upon which technological and engineering solutions are built, fostering a deep understanding of natural phenomena and their applications (National Academy of Sciences, 2014). Technology refers to applying scientific knowledge for practical purposes. It encompasses the tools, processes, and systems developed through engineering practices to solve problems, improve human life, and interact with the environment more efficiently (Feenberg, 2002). The short definition of engineering is the process of designing the human-made world. A more extended definition is the application of scientific principles and mathematical models to design, develop, and innovate technologies and systems that meet human needs. It bridges the theoretical with the practical, turning conceptual ideas into tangible solutions (National Academy of Engineering and National Research, 2009). Mathematics, the language of STEM, provides the essential tools for quantification, problem-solving, and logical reasoning across all STEM disciplines. It enables the analysis and interpretation of scientific data, supports engineering design processes, and underpins technological advancements (English 2015; Maass et al. 2019).

At first glance, the relationship between these elements is symbiotic, with each discipline contributing to and reinforcing the others. Science offers the theoretical basis, technology translates theory into practical applications, engineering provides the methodologies to create those applications, and mathematics offers the tools for analysis and design. Together, they form a cohesive and dynamic educational framework to prepare students to navigate and contribute to a complex, technology-driven world (Sanders, 2009). However, in practice, reality proves to be more complicated.

Even at the level of a basic definition—distinguishing what is considered STEM and what is not—challenges arise. One notable example is the inclusion of social sciences within the STEM designation. Some governmental bodies, educational institutions, and professional associations adopt a broader interpretation of STEM that embraces psychology and the social sciences alongside core sciences like physics, chemistry, and engineering. Other entities adhere to a more restricted definition that generally excludes social sciences, focusing primarily on mathematics, chemistry, physics, computer and information sciences, and engineering (Gonzalez and Kuenzi, 2012). The definition of STEM within specific institutions also evolved. For instance, the US Department of

Homeland Security, which is responsible for issuing visas and determining the job futures of migrants in the USA, expanded its conservative STEM categorisation in 2023 to include Institutional Research, Developmental and Adolescent Psychology, Demography and Population Studies into its STEM framework (Department of Homeland Security, 2023).

The ambiguity surrounding what constitutes the STEM field reflects the broader challenge of fostering an educational model that can adapt to the workforce's and society's evolving demands. The challenge extends beyond mere terminology to the practical implementation of STEM education, affecting curriculum development, teaching methodologies, and student outcomes (Martín-Páez et al., 2019). Herschbach (2011) details the difficulties in defining STEM education and developing a curriculum that genuinely reflects its interdisciplinary ethos. This challenge is exacerbated by the diverse nature of each discipline within STEM.

Science encompasses a range of disciplines, each with its own rigorous and institutionalised traditions, typically grounded in curricula developed over the years. Disciplines such as biology, chemistry, and physics are traditionally taught as distinct subjects. This entrenched separation presents challenges in devising a unified STEM curriculum that accurately reflects the interdisciplinary essence of scientific inquiry (Herschbach, 2011).

Technology and engineering are firmly grounded in applied knowledge, which often presents challenges in school settings due to its highly contextual and specific nature (Feenberg, 2002; Dasgupta, 1996; Pacey, 1999; Skolimowski, 1966). Fields like digital technology rarely feature in primary or secondary school curricula. Engineering, encompassing a variety of specializations like electrical, chemical, environmental, biomedical, or materials engineering, struggles with integration into general education programs outside of vocational training. Technology and engineering are often regarded as domains focused on preparing students for specific careers, thus making it a vocational subject at the collegiate level where its curriculum is tailored to meet the needs of particular occupational fields (Oaks, Leone & Gunn, 2001). While there are claims about teaching general engineering processes in some countries, evidence suggests that realising this goal remains challenging. Only a few educational programs successfully integrate technology and engineering principles as an important curriculum component (Kelley, Brenner & Piper, 2010; Herschbach, 2011). Engineering and technology have yet to integrate into the curriculum both in the US, where the issue is investigated more often (Çetin & Demircan, 2020; Daugherty et al., 2014; Strimel & Grubbs, 2016), and worldwide, including Europe (Ritz & Fan, 2015; Freeman et al., 2014). The prevailing belief that technology and engineering fall under the umbrella of math and science without recognising their distinct contributions is likely mistaken.

With its well-defined subject matter and role as a foundational tool for science, technology, and engineering, even mathematics becomes somewhat problematic in integrating the four concepts that build the STEM acronym. This issue arises from the distinct nature of mathematical education and the challenge of aligning its abstract principles with the applied and interdisciplinary approaches favoured in STEM education. Bridging the gap between the pure theoretical framework of mathematics and its application within the context of science, technology, and engineering education requires innovative teaching strategies and curriculum development that can accommodate the unique characteristics of each discipline while fostering a cohesive learning experience (Maass et al., 2019).

The interpretation of what constitutes STEM education varies significantly across educational levels, adding layers of complexity to its implementation (Breiner et al., 2012). At the primary school level,

STEM education is less about the intensive study of each discipline and more focused on developing foundational competencies such as problem-solving, critical thinking, and collaborative skills, laying the groundwork for future specialised education. At this level, STEM education often mirrors the general curriculum required for all students, focusing primarily on a combination of science and math. As education progresses, the curriculum becomes increasingly specialised, with secondary education offering multiple tracks through required math and science courses alongside electives in fields such as computer science and engineering (Xie et al., 2015). This specialisation continues into higher education, where programs are distinctly categorised as STEM or non-STEM, although educational experiences and outcomes can differ markedly within these categories (Xie & Killewald, 2012; Xie & Shauman, 2003).

It turns out that "STEM education" lacks a clear definition; it is more akin to an open project than a strict concept requiring precise delineation each time. Herschbach (2011), in his insightful analysis of the issue, writes with a concern that should be shared:

> *STEM does not represent a specific curriculum model; rather, there are many ways to formulate STEM programming. In fact, it is hard to discern what exactly is meant by "STEM". Practically any kind of educational intervention that is even remotely associated with science, technology, engineering or math is referred to as a STEM innovation. This lack of a solidifying perception of STEM threatens over the long-term to destroy support for the movement. Failure to deliver results will probably exceed successes. (Herschbach 2011: 98).*

A term that frequently comes to the forefront of any attempt to define STEM is "integration". Indeed, over the last two decades, integration has been the most recurrent theme within the context of STEM and STEM education, a topic we will explore in detail in the following section.

3 Integrated STEM education

Advocates of integrated STEM education highlight its relevance in an evolving economic landscape where the labour market undergoes continuous changes. They argue that conventional education, focused on imparting job-specific skills, is increasingly misaligned with the requirements of this dynamic environment. This misalignment is primarily due to the static nature of traditional educational models, which struggle to adapt to the shifting demands of the economy (Acemoglu & Restrepo, 2019). Many works have underscored this point, illustrating how advancements in automation and artificial intelligence are transforming the job market (Brynjolfsson and McAfee, 2014; Frey and Osborne, 2017; Acemoglu and Restrepo, 2019; Eloundou et al. 2023). These changes make certain specific skills redundant and escalate the need for broader, more flexible competencies.

Proponents of integrated STEM education claim that the mismatch between education and the evolving economy underlines the need for educational frameworks emphasising collaborative problem-solving, creativity, and adaptability. According to supporters of integrated STEM education, these competencies are essential not because they are directly linked to specific jobs but because they equip individuals to effectively engage with and contribute to diverse, changing professional landscapes. Highlighting these skills over job-specific ones recognises the future workforce's reality, where continual change is inevitable, and the ability to adapt is crucial for both personal and professional achievement, as noted by Honey & Shaw (2012) and Sanders (2009). Moreover, adopting an integrated STEM curriculum is highlighted as a beneficial strategy, offering learners experiences that are more relevant, cohesive, and engaging. This approach acknowledges that real-world challenges do not conform to the isolated disciplinary boundaries often found in educational settings. Instead, complex problems require skills across various disciplines, underscoring the necessity for an educational model that reflects the interconnected nature of knowledge and application in the real world (Kurner and Kumar, 2007).

Sanders' (2009) definition of integrated STEM education is likely the most frequently cited one. It stresses the importance of a cohesive and integrated methodology. Rather than considering STEM disciplines in isolation, they are presented as interconnected domains that mirror the intricacy of real-world issues. Sanders posits that this integrated approach is crucial for nurturing students' capacity to apply knowledge in a holistic manner, thereby enhancing their comprehension of the interplay and mutual impact among these disciplines. Furthermore, integrating STEM education and focusing on broad competencies align with the understanding that the future of work will rely heavily on interdisciplinary knowledge and the ability to innovate within rapidly changing technological landscapes. By fostering an education system that values adaptability, problem-solving, and creativity, we prepare students for today's jobs and for the creation and adaptation to the jobs of tomorrow. Advocates of integrated STEM education stand for an educational framework that equips students with a robust set of transferable skills, emphasising the importance of adaptability, continuous learning, and cross-disciplinary thinking in the face of technological advancements and labour market transformations.

The literature outlines varying levels of disciplinary integration, ranging from multidisciplinarity through interdisciplinarity to transdisciplinarity (Holbrook et al., 2020). In a multidisciplinary approach, various disciplines contribute their insights independently without integrating these contributions into a cohesive whole. On the other hand, interdisciplinarity encourages collaboration among different disciplines, aiming for the synthesis and integration of knowledge, though it remains led by distinct disciplinary perspectives and methodologies. Transdisciplinarity distinguishes

itself by moving beyond these confines, challenging the division of knowledge into separate disciplines. It seeks a more holistic approach that integrates and transcends traditional academic boundaries to address complex issues comprehensively (Choi & Pak, 2006; Montuori, 2008; McGregor, 2015).

In discussing STEM integration, the distinction between “correlated curriculum” and “broad fields curriculum” emphasises different approaches to interdisciplinary teaching (Herschbach, 2011). The “correlated curriculum” focuses on collaboration across disciplines without merging them, requiring intensive coordination to ensure concepts are relevant and timely across subjects. This approach requires minimal adaptation from traditional instructional programs, emphasising the need for ongoing coordination among disciplines to ensure the relevance and application of concepts across subjects. In practice, it necessitates extensive coordination and planning across various subjects, with high collaboration among teachers. Effective implementation requires modifying the conventional organisation of subject fields to ensure coherence and timeliness in integrating concepts across disciplines. This approach may involve significant changes in how subjects like algebra are taught, ensuring concepts align with the needs of other disciplines such as physics and engineering. While facilitating interdisciplinary connections, the correlated curriculum model does not provide a clear vision for addressing attitudes, developing transversal skills, or enhancing technological and engineering competencies.

The “broad fields curriculum” integrates related subjects into a unified field of study, blending individual subjects into a coherent instructional framework. This approach organises education around clusters of related disciplines, such as combining aspects of arts, science, and technology into integrated courses. The challenge lies in creating an effective organising structure that preserves elements of the original disciplines while facilitating an interdisciplinary learning experience. The task of building and programming a robot for a specific task exemplifies this method, engaging students in applying a range of knowledge to real-world problems, thereby emphasising the importance of maintaining fundamental knowledge and skills within this integrated approach.

Given the rationale for integration, as stated by Kurner and Kumar (2007), which emphasises that solving complex problems necessitates skills spanning various disciplines to mirror the interconnectedness of knowledge and its real-world application, some educators and educational researchers have taken this argument further. They justifiably argue that technical problems do not exist in a vacuum but are deeply embedded within social and ethical contexts. According to some educational specialists, it is essential to incorporate a binder that utilises arts to achieve true and comprehensive integration of STEM subjects, and later discussions have also included the humanities. This approach is crucial for optimising functioning within society, suggesting that for STEM education to be fully integrated and reflective of real-world challenges, it must embrace and incorporate the broader perspectives offered by arts and humanities. This enriched educational framework ensures that learners are not only proficient in technical skills but are also equipped with transversal skills, like creativity, problem-solving, and collaboration, as well as the social and ethical understanding necessary for addressing complex problems holistically and responsibly (Kim et al., 2019; Zeidler,2016).

4 Arts and STEAM education

The exact origins of STEAM are subject to discussion. Leavy and colleagues (2023) note that the term STEAM was first coined by Georgette Yakman in 2006, written as STΣ@M. Yakman's concept of STEAM aimed to create a cohesive curriculum that effectively merges the STEM fields with the arts, advocating for a more integrated approach to education (Yakman, 2008; Yakman & Lee, 2012). Babette (2017), on the other hand, suggests that the STEAM acronym first gained public recognition in 2009 through a Florida Alliance for Arts Education statement (Florida Department of Education, 2009), highlighting that the insertion of arts into the STEM curriculum is not merely an educational enhancement but a strategic approach to foster creativity, critical thinking, and innovation. This aligns with the broader educational shift towards integrating 21st-century skills, such as critical thinking, problem-solving, and digital literacy (Kennedy & Sundberg, 2020; Holbrook et al., 2020), into teaching and learning practices. The Florida statement underscored the importance of arts in stimulating comprehensive cognitive and affective student outcomes, paving the way for a more holistic educational model that appreciates the interconnectivity of disciplines and the value of diverse ways of thinking and problem-solving in preparing students for the complexities of the modern world (Florida Department of Education, 2009).

While the overarching concept behind integrated STEM education and its STEAM extension may seem straightforward, the intricacies of their conceptualisation remain far from clear. STEAM education confronts several ambiguities and conceptual opacities in terms of its terminology, pedagogical methods, and research foundations (Aguilera & Ortiz-Revilla, 2021; Colucci-Gray et al., 2017; Matsuura & Nakamura, 2021). The interpretation and integration of arts within this framework exhibit a wide range of perspectives and methodologies. Some academics narrowly interpret the “A” in STEAM, associating it solely with visual arts, such as painting, sculpture, and photography. While some advocate for a broader inclusion, encompassing visual and performing arts, crafts, and other expressive disciplines (National Art Education Association, 2016), others extend this inclusion even further to liberal arts, humanities (Quigley et al., 2017), or all non-STEM fields of study including basically all possible knowledge into a STEAM concept (Zeidler, 2016). In another vein, some view “arts” within STEAM as synonymous with project-based, technology-driven, or design-oriented activities (Perignat & Katz-Buonincontro, 2019).

Aguilera and Ortiz-Revilla (2021) articulate this ambiguity in their systematic literature review, summarising the current state of conceptualisation as follows:

> *The literature has once again demonstrated that both STEM and STEAM education lacks a clear conceptual framework with broad consensus within the scientific-educational community. In this sense, the possibilities of implementing this approach in practice and the rigorous evaluation of its educational potential are diminished. In addition, it highlights an obligation upon the scientific community to increase the number of studies of an experimental nature in order to determine whether STEM and STEAM education have the capability to develop the creativity of students.*

Similarly, Mejias et al. (2021) reflect on the nascent state of STEAM, indicating that:

> *Yet, as with many nascent fields, the conceptualization and usage of STEAM is somewhat ambivalent and weakly theorized. On the one hand, STEAM offers significant promise through its focus on multiple ways of knowing and new pathways to equitable Learning.*

On the other hand, it is often deployed in theory, pedagogy, and practice in ambiguous or potentially problematic ways toward varying ends.

These observations underscore the dynamic yet unsettled nature of STEAM education's theoretical underpinnings, suggesting a field with potential that still needs a more precise definition and empirical validation.

Perignat and Katz-Buonincontro (2019), in their examination of STEAM literature, identified recurring patterns in its definition, consistent with observations in other scholarly works. They demonstrated that two primary branches of definition emerged. Half of the articles covered in their review (22) delineate STEAM education to engage students in STEM learning, fostering creativity, or enhancing problem-solving skills within real-world contexts. Meanwhile, the second approach underscores the importance of integrating domain-general skills, such as perspective-taking, creativity, problem-solving, and knowledge transfer across disciplines, and encouraging students to explore and experience new paradigms of understanding.

To summarize, it can be generally assumed that the approach regarding “A” in STEAM can be described in two directions. Namely, it can emphasize Attitudes (supporting motivation, interest, and ethical dimension) or Additional skills (building transversal skills such as collaboration and critical thinking). In simpler terms, when “A” appears in the STEM literature, it underscores the importance of one or both elements in integrated STEM education.

5 STEM education outcomes: literacy, competencies, knowledge, skills, and attitudes

The integrated approach of STEM and STEAM has also problematised the analysis of educational outcomes. The definition of STEM proficiency in education is complex and multi-level, ranging from broad formulations such as STEM literacy and competencies to detailed aspects of STEM knowledge, skills, and attitudes. Additionally, there is an emphasis on 21st-century transversal skills (21CS), considered essential outcomes of STEM education. These skills, which include critical thinking, creativity, collaboration, and communication, are integral to preparing students for the challenges and opportunities of the future workforce and society.

According to the National Science Foundation (Bybee, 2010; National Academy of Engineering and National Research Council, 2014), STEM literacy is defined by awareness of the nature of science, technology, engineering, and mathematics and familiarity with some of the fundamental concepts from each discipline, which should be an educational priority for all students.

The Washington STEM Study Group (2011) characterised STEM literacy as the capacity to utilise knowledge from multiple disciplines to address complex challenges that surpass the boundaries of a singular field of study. This literacy requires mastery in each STEM area, including essential concepts, procedures, and attitudes and recognising their interconnections. Achieving STEM literacy means understanding the world through these disciplines and applying this knowledge to enhance social, economic, and environmental conditions across all societal spheres.

Another broad definition of STEM competencies comes from the 2018 Council of the European Union's recommendation on key competencies for lifelong learning, encompassing the integrated abilities across mathematics, science, technology, and engineering. According to the recommendation, STEM competencies empower individuals to engage with quantitative reasoning, scientific exploration, and practical problem-solving across various domains, implicitly indicating the need for integration of STEM subjects, which is essential for addressing real-world challenges and contributing to innovation and progress (The Council of the European Union, 2018).

On more detailed levels, literacy or proficiency in STEM competencies can be defined as knowledge, skills, and attitudes (see Table 1). As the Council of the European Union proposed in 2018, this approach encompasses mathematical, scientific, technological, and engineering domains. Mathematical competence, for instance, includes not just mastery of numeracy but also the ability to apply mathematical thinking in various contexts, supported by a thorough understanding of numbers, operations, and mathematical concepts. Similarly, science, technology, and engineering competencies combine substantive knowledge of the natural world and technological processes with the skills to investigate, analyse, and apply this knowledge. Attitudes within STEM competencies embody a crucial dimension, reflecting an individual's mindset and approach toward learning and applying STEM knowledge. These include a respect for truth, a willingness to seek and evaluate causes, curiosity about scientific and technological advancements, a conscientious stance on ethical, safety, and environmental sustainability issues, and adherence to the scientific method.

Table 1. STEM Competencies Summary

Domain	Knowledge	Skills	Attitudes
Mathematics	Understanding of numbers, operations, mathematical concepts.	Applying mathematical principles in various contexts.	Respect for truth, willingness to evaluate validity.
Science	Fundamental principles of the natural world, scientific methods.	Investigation through methodologies, evidence-based conclusion drawing.	Curiosity, ethical concern, support for safety and sustainability.
Technology	Principles, impacts of technology on the natural world.	Use of technological tools for evidence-based decisions.	Critical appreciation, responsibility towards environmental and societal impacts.
Engineering	Engineering principles and their application to solve problems.	Designing, building, and testing solutions to real-world problems.	Ethical considerations in design and implementation.

Source: Own, based on Key Competences for Lifelong Learning (EU 2018).

The final part necessary to describe STEM skills is transversal skills, often referred to as 21st-century skills. These skills are essential for integrative STEM and STEAM education, aligning with broad definitions of STEM competencies by The Washington STEM Study Group and the European Union's Recommendation. These skills include critical thinking, communication, collaboration, and creativity, forming a core part of the educational framework that prepares students for modern society and economy. They emphasise the need for education systems to proactively adapt to rapid societal and technological changes by fostering skills that are not only applicable across various disciplines but also vital for innovation and problem-solving in complex, real-world situations.

Although there have been numerous attempts to define 21st-century skills, and researchers have yet to reach a consensus on a definitive list, the effort by the US National Education Association and the Partnership for 21st-Century Skills (National Education Association, 2012) stands out as one of the most influential (Kennedy et al. 2020). The framework identified 18 skills essential for educational standards, professional development, and assessments. This framework, deemed overly complex over time, was later streamlined to focus on the “four C's”: critical thinking, communication, collaboration, and creativity, reflecting a refined understanding of critical educational priorities (Partnership for 21st Century Skills, 2010, 2015). In 2012, the US National Research Council (NRC) also categorised 21st-century skills to clarify across-skill relationships and support their development, organising them into cognitive, intrapersonal, and interpersonal domains (NRC, 2012).

Table 2. Competency Categories, National Research Council

Cognitive Domain	**Intrapersonal Domain**	**Interpersonal Domain**
Cognitive processes/strategies	*Intellectual openness*	*Teamwork/collaboration*
• Critical thinking • Problem solving • Analysis • Reasoning and argumentation • Interpretation • Decision-making • Adaptive Learning	• Flexibility • Adaptability • Artistic and cultural appreciation • Personal and social responsibility • Appreciation for diversity • Adaptability • Continuous Learning • Intellectual interest and curiosity	• Communication • Collaboration • Cooperation • Teamwork • Coordination • Interpersonal skills
Knowledge	*Work ethic/ conscientiousness*	*Leadership*
• Information literacy • ICT literacy • Oral and written communication • Active listening	• Initiative • Self-direction • Responsibility • Perseverance • Grit • Career orientation, ethics • Integrity • Citizenship • Responsibility	• Assertive communication • Self-presentation • Social influence with others
Creativity	*Positive core self-evaluation*	
• Creativity • Innovation	• Self-monitoring • Self-evaluation • Self-reinforcement • Physical and psychological health	

Source: Kennedy and Sundberg (2020: 486).

Interestingly, we have a broad picture of 21st-century skills, although it is evident that we are struggling with detailed definitions:

> *We are 20 years into the 21st century and we are still struggling to define 21CS with precision due to the dynamic nature of the skill sets necessary for success. These definitions will undoubtedly evolve as we move into the 22nd century. (Kennedy and Sundberg, 2020).*

6 Navigating today's landscape of STEM education: a summary attempt

STEM education, originally developed to meet the needs of a technologically evolving workforce and economy, has evolved from focusing solely on science, technology, engineering, and mathematics to including an integrated approach and further to STEAM, which adds the arts. This evolution reflects a shift from traditional educational frameworks towards ones that prepare students more holistically for real-world challenges, which are often interdisciplinary. The integrated STEM approach emerged from the understanding that real-world problems do not conform to the strict boundaries of single disciplines, advocating for education that fosters interdisciplinary learning and problem-solving. The further transition to STEAM emphasises the role of creative thinking and innovation, integrating arts to enhance problem-solving skills and acknowledge the importance of social and ethical contexts in technical solutions. This approach aims to provide a more comprehensive education combining technical skills, creativity, ethics, and collaboration.

The keyword to today's understanding of STEM for most scientists and educators is likely “integration”, yet there is a dramatic lack of common understanding of this concept, sometimes even at a basic level, regarding what is considered science and what is not. Furthermore, there is confusion about how to integrate STEM subjects or what educational outcomes modern STEM education should deliver to students and citizens. Consequently, we must navigate using a few ambiguous indicators of this approach. Thibau and colleagues (2018), in their systematic review of instructional practices in secondary education, proposed five key indicators (calling them principles) underlying the integration of STEM concepts:

- **Integration of STEM content** principle emphasizes the need for clear incorporation of learning objectives, content, and practices across different STEM disciplines. Authors acknowledge the existing terminology confusion and avoid prescribing a specific strategy.
- **Problem-centred learning** principle highlights the importance of engaging students in authentic, complex, real-world problems.
- **Inquiry-based learning** principle advocates for learning environments that stimulate students' curiosity and involvement in experiential learning and hands-on activities.
- **Design-based learning** principle involves presenting students with open-ended design challenges that introduce them to engineering design processes and practices and deepen their understanding of core disciplinary ideas.
- **Cooperative learning** principle emphasises the importance of communication and collaboration among students to enhance their learning experience.

The core principles are, of course, compatible with educational methods recognised as indicative of an integrated STEM approach (Kennedy & Sundberg 2020):

- **Project-based learning** involves students engaging in projects that address real-world problems, requiring interdisciplinary knowledge and collaboration to devise effective solutions, thereby emphasizing the practical application of STEM concepts in tangible scenarios.

- **Problem-based learning,** closely related, focuses on the process of solving complex and often ambiguous problems, fostering critical thinking and problem-solving skills by applying theoretical knowledge to practical situations.
- **Phenomenon-based learning**, starts with observation of a phenomenon, which could be anything interesting and complex enough to study further. This method promotes curiosity and encourages an inquiry-based approach to learning, where students synthesise information from various sources to gain a comprehensive understanding of complex subjects.

The Integrated STEM or STEAM education is underpinned by a **social constructivist approach to learning**, which emphasises that students actively build their knowledge through their pre-existing notions and experiences (Driver et al., 1994; Eastwell, 2002) and that learning is a communal activity rather than an individual experience (Prawat and Floden, 1994). The social constructivist theory, though not frequently directly referenced, serves as the main theoretical foundation of the integrated STEAM education movement.

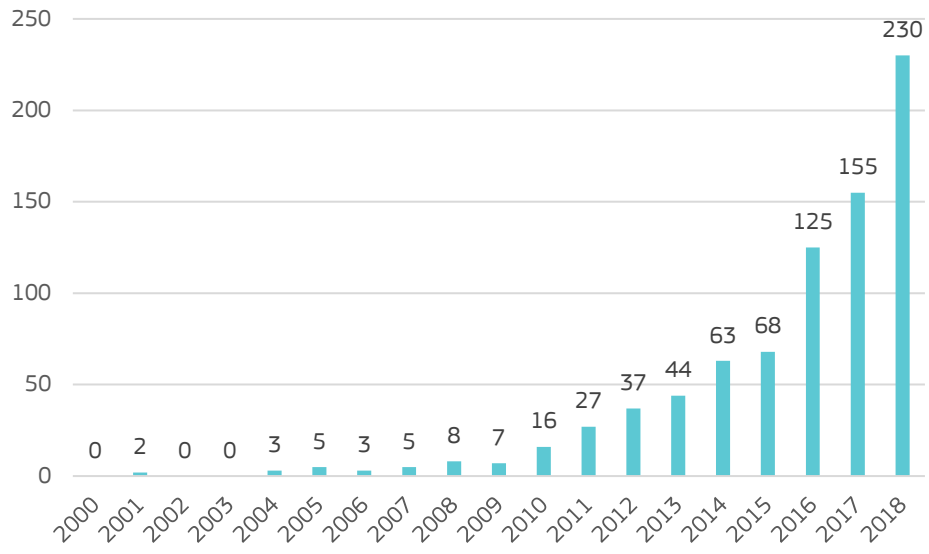
Integrated STEM education is also defined by a **complex (often not precisely defined) skill set.** This characterisation reflects the interdisciplinary nature of STEM fields, where the integration extends beyond academic knowledge to include various cognitive, social, and technical skills. The challenge lies in teaching these skills and defining and assessing them in a way that reflects their interconnectedness and relevance to real-world applications.

While the term “integrated STEM” has become dominant in the scientific discourse and literature, it's important to remember that not all educational researchers, policymakers, or teachers are moving towards an integrated approach. Instead, many continue to focus on developing STEM as a multidisciplinary project, concentrating on individual subjects like mathematics, physics, and biology. This approach sees value in deepening expertise within each discipline rather than blending them. A notable trend in European secondary education programs in recent years exemplifies this, with an increasing number of countries moving away from integrated science curricula towards more discipline-specific teaching (Horváth et al., 2022). This shift suggests a belief in the importance of foundational knowledge in individual STEM fields, potentially offering a more granular understanding and mastery of each area. This approach, while differing from the integrated model, underscores the diversity in educational strategies to prepare students for the complexities of the modern world, where both depth and interdisciplinary knowledge play critical roles.

7 What does research tell us about STEM and STEAM education and outcomes?

Research in education has extensively explored the teaching of specific subjects, particularly mathematics (National Council of Teachers of Mathematics, 2014; Blazar, 2015; Miao and Reynolds, 2017) and various science disciplines (Wise and Okey, 1983; Cimer, 2007; Johnson et. al., 2007), revealing substantial insights into effective teaching strategies, curriculum development, and student learning outcomes in these fields. Studies have delved into the nuances of subject-specific pedagogies, the integration of technology, and the impacts of teacher knowledge and beliefs on student achievement. However, comparatively little is known about the holistic approach to STEM education and comprehensive STEM education programs. This situation is changing, and the interest in STEM education among researchers is growing, as shown by the increasing number of studies published on this topic. In their systematic review, Li et al. (2020) looked at 798 journal articles published between 2000 and 2018 in 36 journals (see Figure 1). The analysis encompassed quantitative and qualitative examinations of the selected journals, including the volume of articles published, the diversity of journals featuring these articles, the nationality of authors, and the evolution of research topics and methodologies over the years.

Figure 1. Number of articles on STEM education by year



Source: Li et al. 2020: 7.

According to the study's method, about 75% of the articles on STEM education come from the USA. Following the USA, the countries contributing the most to STEM education research are Australia, Canada, Taiwan, and the UK, while little evidence stems from the European Union (EU27).

An even more intriguing and somewhat surprising discovery is that most articles, which account for almost half of the publications (375, 47%), are not research articles but primarily discussions or summaries that do not expand our scientific knowledge around the topic. This could explain our limited understanding of STEM and STEAM education. Without a substantial body of research-based articles, our knowledge of effective practices, outcomes, and impacts in STEM and STEAM education is based more on theoretical or conceptual discussions than empirical evidence. This highlights a

gap in the literature and suggests a need for more research-based studies to deepen and broaden our understanding of STEM and STEAM education.

While we have a relatively small number of research studies available on the efficiency of different STEM programs, this selected body of research indicates the positive effects of integrated STEM education across various areas. Research conducted in various disciplines reveals that students engaged in an integrated curriculum often perform as well as, or even better than, their counterparts in traditional instruction that separates disciplines (Czerniak et al., 1999; Hinde, 2005). Additionally, adopting an integrated curriculum has enhanced students' non-cognitive learning outcomes. For instance, it can increase students' interest in STEM subjects (Mustafa et al., 2016; Riskowski et al., 2009) and boost their motivation towards learning STEM (Wang et al., 2011).

Becker et al. (2011) aimed to investigate the effects of integrated STEM education on students' learning. They conducted a meta-analysis of 28 studies, and their results indicate that integrative curricula positively affect student learning, with the largest effect size observed at the primary school level and the smallest at the college level. The analysis also revealed variations in effect sizes across different grade levels and types of integrative curricula, suggesting a need for better data and further investigation. The authors acknowledge limitations due to the small number of studies and the lack of empirical data on STEM education research.

Gresnigt et al. (2014) examined integrated curricula in primary education from 1994 to 2011 to understand their advantages and disadvantages and their impact on learning outcomes. The study found that integrated curricula generally increased time spent on science, with positive cognitive and motivational effects reported in most projects. Additionally, students displayed improved attitudes toward science and increased motivation. Moreover, the review highlighted the increased time allocated for science and technology in classrooms using integrated curricula.

The evidence for STEAM is more fragmented and weaker. The review by Perignat and Katz-Buonincontro (2019) analysed 44 articles on STEAM education spanning from 2007 to 2018. It underscored the diversity in defining STEAM education's goals and the integration of arts, noting an absence of consistent definitions and articulated learning outcomes, particularly in fostering creativity and problem-solving abilities. The review categorises integration methods into transdisciplinary, interdisciplinary, multidisciplinary, cross-disciplinary, and arts integration, offering insights into the disparate approaches to combining STEAM disciplines. It calls for more rigorous research and practical strategies to refine STEAM educational practices. Echoing these sentiments, Leavy et al. (2023) highlighted a similar oversight in evaluating learning outcomes within STEAM education, particularly the underassessment of arts and 21st-century skills. This gap points to a broader issue in the literature regarding the need for more effective assessments to ensure educational interventions meet their intended outcomes in STEAM fields.

8 What does research tell us about STEM education and outcomes in EU27?

Regarding national and European educational outcomes, large-scale assessments are the primary data sources, as the previously mentioned studies are limited in scope, being either experimental or observational with a small, defined population. Large-scale assessments, which will be discussed in more detail later in this document, examine elements of STEM, including mathematical skills, general science abilities (as seen in the Organisation for Economic Co-operation and Development's Programme for International Student Assessment, PISA), and sometimes more specific subject skills related to the STEM acronym (as in the Trends in International Mathematics and Science Study, TIMSS). However, they largely leave out elements related to Engineering, Technology, and transversal skills from their main areas of interest. For Science and Mathematics, we have representative studies concerning school populations (PISA, TIMSS) and adults (PIAAC).

In the European Union, a considerable number of students fail to reach basic achievement levels, which is above the agreed maximum target of 15% (Council of the European Union, 2021). According to TIMSS 2019, the percentage of low achievers in grade 4 mathematics and science was above 15% in all participating education systems. Latvia, the Netherlands, Ireland, and Austria had the lowest percentage of low achievers in mathematics, while France had the highest percentage of low achievers. In terms of secondary education (as measured by PISA 2018), only a few education systems could meet the under 15% target for low achievers in mathematics, with Estonia, Denmark, Poland, and Finland showing notable success. However, most systems still struggle with high rates of underachievement, particularly in mathematics and science, indicating the need for interventions to improve student outcomes (Horváth et. al., 2022).

Compared to the 2018 PISA results, the underachievement rate in mathematics and science in 2022 has increased: about 30% of EU students do not reach a minimum proficiency level in mathematics, and 25% do not in science. Almost 50% of all students from disadvantaged backgrounds underachieve in mathematics. The share of top performers is continuously decreasing. Furthermore, PISA data also highlights that the COVID-19 crisis has worsened educational outcomes and increased educational inequalities (EU, 2024).

Both PISA and TIMSS data indicate that socioeconomic status significantly influences educational outcomes. Students from disadvantaged backgrounds are more likely to underachieve, and this disparity becomes more pronounced as individuals transition from adolescence into early adulthood. Individuals from lower socio-economic backgrounds face increased challenges in improving or maintaining their literacy and numeracy proficiency compared to their more advantaged peers (Borgonovi, 2017).

Gender differences in achievement are also visible in TIMSS and PISA for EU27 countries. TIMSS results for primary education indicate minimal gender disparities (Horváth et al., 2022). However, in PISA mathematics, the gender gap in favour of boys among average-performing students corresponds to one-tenth of a standard deviation, but it increases to one-fifth of a standard

deviation[1] at the top decile of the country-specific mathematics performance distribution. In science, no gender gap can be observed among average-performing students, while boys appear to be over-represented at both the top and the bottom tail of the science performance distribution (OECD, 2015).

Based on the Eurydice Report (Horváth et al., 2022), our understanding of science and mathematics education and policy orientations across EU27 has been enriched. This analysis reveals that science is approached as a cohesive subject in primary education across nearly all European countries. Yet, as students progress to lower secondary education, the curriculum predominantly shifts towards specialised instruction in distinct science disciplines such as biology, physics, and chemistry. This shift marks a notable increase in the focus on discipline-specific science education compared to a decade ago, with several countries moving away from the integrated science model in compulsory education stages. The findings contrast the prevailing discourse in the literature surrounding STEM and its expanded counterpart, STEAM. This body of research largely advocates for an integrated approach to teaching these disciplines, emphasising the benefits of blending scientific, technological, engineering, and mathematical concepts with creative arts. The move by several European countries towards a more compartmentalised, discipline-specific model of science education in lower secondary education, as reported by Horváth and colleagues, seems at odds with these recommendations. This might not be surprising as empirical evidence supporting the efficacy of integrated STEAM education remains inconclusive, with studies on its long-term impacts on student learning, engagement, and future career paths still evolving.

The Eurydice report also shows that structuring science education across school grades typically encourages a unified science teaching approach during the initial 4-6 years of compulsory education, often aligning with the duration of primary education. Following this phase, the curriculum usually transitions into 2-4 years of focused instruction on individual science subjects during lower secondary education. Instructional time allocations reveal a pattern where mathematics is emphasised more during primary education, contrasting with secondary education, where science gains more instructional focus (Horváth et al., 2022).

Regarding assessment practices, there appears to be a greater emphasis on mathematics in primary education assessments across Europe, with most education systems conducting national mathematics tests for all students. Conversely, less than a third of European education systems carry out national science tests as an integrated subject, often on a sample basis. However, at the secondary education level, the balance between mathematics and science assessments becomes more equitable, with over a third of education systems administering certified exams and/or national tests in specific science subjects such as biology, physics, and chemistry (Horváth et al., 2022).

To enhance student motivation in mathematics and science, more than half of the European countries have reported national strategies, programs, and other initiatives beyond the curriculum. These initiatives often focus on enriching the learning experience through specialised workshops,

[1] Avvisati and Givord (2022) showed that yearly learning progress around the age of 15 varies from about one-tenth to about one-fourth of a standard deviation in students' test scores.

guest professional interactions, clubs, and extracurricular activities. In Germany, the Standing Conference of the Ministers of Education and Cultural Affairs focuses on MINT subjects, introducing educational standards that define competences. Italy's 'Science Education' project emphasises enquiry-based laboratory teaching. Austria's 'Innovations make schools great!' initiative improves teaching in various subjects and supports teachers with expert guidance. Slovenia's 'NA-MA Poti' project and Finland's LUMA Centre develop pedagogical approaches and support lifelong learning for teachers in STEM. In Czechia, Spain, and Portugal, schools enrich learning with extracurricular or school-day activities involving external professionals. Andalucía's STEAM project integrates aerospace research into primary and secondary education curriculums. The Croatian Makers Movement's extracurricular STEM program engages over 200,000 children, providing them with access to technology and encouraging discovery (Horváth et al., 2022).

9 Challenges of STEM education

The empirical results described above lead to the main challenges that the EU27 must face. First, many students across the EU fail to achieve basic proficiency levels in key STEM areas, particularly mathematics and science. Underachievement rates exceed the target threshold, with significant numbers of students not meeting minimum proficiency levels. This challenge is exacerbated by educational disruptions due to the COVID-19 pandemic, which have worsened outcomes and deepened educational inequalities.

Second, Horváth et al. (2022) highlight a prevalent challenge across most European education systems: a shortage of qualified mathematics and/or science teachers in all educational stages. This shortage leads to a discrepancy between the actual teaching practices and the standards outlined in official guidelines, with many educators lacking the requisite subject specialisation or pedagogical training for these disciplines. Several countries have implemented measures such as professional development opportunities and introducing new courses or additional study spaces for prospective mathematics or science teachers to address these issues. Supporting this, data from the TIMSS 2019 survey underscores the significant demand for professional development among current science and mathematics teachers, particularly emphasising a stronger need for science.

Third, the share of top performers in STEM subjects is continuously decreasing, and a significant portion of students from disadvantaged backgrounds underachieve, especially in mathematics. This widening talent gap suggests a need for targeted interventions to cultivate and support high achievers and provide additional support where it is most needed.

Finally, the transition in educational approaches from integrated science in primary education to more specialised discipline-specific education at secondary levels might reflect broader educational policy shifts. However, this could impact community perceptions and support for an integrated STEM (or STEAM) approach, emphasising the interconnection between sciences, technology, engineering, arts, and mathematics. Building community awareness and support for comprehensive STEM education is crucial to fostering a supportive environment that values interdisciplinary learning and innovation.

In summary, the main challenges are:

- Improving students' and citizens' engagement, participation, and accomplishments in STEM disciplines;
- Providing students and citizens more opportunities to engage with competent and influential STEM educators and leaders;
- Tackling and narrowing the disparities in students' STEM talent and skills;
- Raising community consciousness and encouraging backing for STEM projects.

The main challenges identified above set forth key objectives, which align with the goals proposed by the Tennessee STEM Innovation Network (2012) to accelerate STEM talent development:

- Increase student interest, participation, and achievement in STEM;
- Expand student access to effective STEM teachers and leaders;
- Reduce STEM talent and skills gaps;

- Build community awareness and support for STEM.

This perspective is a comprehensive and agreeable representation of the issue, summarising the main problems identified in various academic papers and political responses. However, before these goals can be pursued, it's necessary to consider foundational objectives that must be addressed to pursue the policy goals:

- Define the specific outcomes that we aim to measure;
- Develop or adapt tools for measuring defined outcomes;
- Identify which educational practices and programs are effective;
- Evaluate the feasibility of implementing educational practices and programs.

Approaching the problem in this structured manner and focusing on foundational objectives is crucial for successfully realising broader political and educational goals in STEM fields.

9.1 Define the specific outcomes that we aim to measure

The challenge of defining STEM concepts and the outcomes we aim to measure is significant. According to Martín-Páez et al. (2019), a notable portion of studies fails to clearly articulate what specific STEM concepts they are investigating. This ambiguity in defining STEM concepts presents a primary obstacle in STEM education research. Precise definitions are crucial for setting clear research objectives, developing curriculum, and assessing educational outcomes. The challenge of defining STEM concepts extends even to the basic level, for example, determining what constitutes the sciences. This complexity underscores the necessity of providing explicit definitions of STEM. Without a clear understanding of what constitutes STEM education, measuring its effectiveness, identifying improvement areas, or communicating findings and best practices within the educational community becomes difficult. Therefore, explicit definitions of STEM concepts should be a prerequisite for any discourse in research or policy discussions they are necessary to ensure clarity and foster a common understanding essential for advancing STEM education.

9.2 Develop or adapt tools for measuring these defined outcomes

The second challenge involves creating or adapting measurement tools for the outcomes that have been defined. The complexity of STEM education, which integrates knowledge and skills across science, technology, engineering, and mathematics, makes it particularly challenging to assess it. Traditional assessment methods may not adequately capture the breadth and depth of STEM competencies, especially regarding skills that require applying knowledge in novel contexts. The interdisciplinary nature of STEM also means that competencies are diverse and evolving with advancements in each field. Developing or adapting instruments that can accurately measure these outcomes requires innovative approaches beyond conventional testing methodologies.

9.3 Identify which educational practices and programs are effective

Investigating which educational practices and programs enhance desired outcomes presents another challenge. There is no clear consensus on the best practices for integrated STEM education, and the absence of systematic reviews focusing on instructional practices further exacerbates this

issue. Understanding which practices are most effective is essential for designing and implementing STEM programs that engage students and significantly improve their knowledge, skills, and attitudes towards STEM fields. This requires a comprehensive review of existing educational practices and programs and rigorous evaluation methods to determine their impact on student outcomes.

As Herschbach (2011) notes, the STEM education project presents certain contradictions worldwide. On one hand, there's an integrated, application-focused approach suitable for technology and engineering. On the other hand, a structured, theory-focused approach instead is essential for the sciences and mathematics. The unanswered question that Herschbach underscores is how to navigate this educational landscape. The dilemma remains on how to teach additional skills, focus on engineering and technologies, foster positive attitudes, and yet not lose the foundational knowledge traditionally taught in subjects like mathematics, biology, chemistry, physics, and other natural sciences.

9.4 Evaluate the feasibility of implementing educational practices and programs

Assessing the feasibility of implementing STEM educational practices and programs in educational settings is crucial to determine if the educational system is equipped to support them. This includes resource availability, teacher training, curriculum flexibility, and institutional support. The feasibility challenge also encompasses the broader educational policy and socio-economic context, which can significantly influence the implementation of STEM education initiatives. Ensuring that desired outcomes are achievable requires effective instructional practices, measurement tools, and a supportive educational ecosystem to sustain and scale successful STEM education models.

The transition from a traditional, segregated, and discipline-based educational structure to an integrated STEM approach necessitates profound curriculum and lesson planning changes. This challenge involves redesigning the educational framework to support interdisciplinary learning, which is a complex process due to the established nature of current educational systems (Nadelson and Seifert, 2017).

Integrated STEM education demands extensive resources, including materials (e.g., construction tools, electronic and design materials) and human capital (such as teacher training and development). Creating an environment that supports integrated STEM teaching and learning can be costly and time-consuming. This challenge is compounded by the need for teachers to have specialised knowledge in STEM disciplines and pedagogical skills to effectively teach this content. Many teachers feel underprepared to implement STEM applications, indicating a significant gap in teacher training and resources (Hardy, 2001; Nadelson and Seifert, 2017; El-Deghaidy and Mansour, 2015).

Integrating STEAM education focusing on arts is also problematic. We do not have a large body of literature on that. One interesting example is the study by Herro & Cian (2018), where the authors conducted a qualitative longitudinal study involving 33 math and science teachers implementing STEAM programs in their classrooms. The study unveils instructional challenges, encompassing pacing/time, student comprehension of content and processes, planning intricacies, concerns regarding school district policies, technology integration, and assessment-related matters. 21 teachers identified challenges faced by their students in comprehending STEAM activities. Some students struggled with self-directed inquiry and collaborative problem-solving, relying heavily on

teacher guidance. Others found it challenging to grasp the presented content or concepts, hindering their engagement and learning progress. 17 teachers encountered challenges in planning STEAM projects aligned with disciplinary content or collaborating with colleagues less familiar with STEAM education. Difficulties aligning disciplines and ensuring transdisciplinary teaching often arose, underscoring the importance of cohesive planning among educators from various disciplines. Policy-related challenges affected 16 teachers, primarily concerning the pacing of implementation, assessment, and funding issues dictated by district mandates. These challenges sometimes compromised the authenticity of problem-solving through STEAM instruction, as teachers found themselves constrained by mandatory curricular units, testing schedules, or resource limitations. 13 teachers cited technology-related challenges, including unreliable internet access, blocked websites, and limited device availability, which hindered the seamless integration of technology into STEAM activities. Access issues, rather than teacher or student proficiency, posed the most significant challenge. 10 teachers discussed the complexities of assessing STEAM learning, particularly in evaluating group work and ensuring fair individual assessments. The shift towards collaborative work and student-led discussions necessitated re-evaluating assessment strategies to accurately measure student progress and understanding.

9.5 Improving students' and citizens' engagement, participation, and accomplishments in STEM disciplines

STEM education is important for economic development and critical in combating misinformation and underscores the importance of developing competencies for evaluating scientific information critically (Osborne & Pimentel, 2023). Research supporting this goal should focus on identifying barriers to engagement in STEM and effective strategies to overcome these obstacles. Studies could explore the impact of early exposure to STEM activities, the role of informal learning environments, and the effectiveness of different teaching methodologies in enhancing STEM learning outcomes. Also, more research is needed to understand how educational programs should be constructed to increase general accomplishments in STEM subjects (Eisner et al., 2019). Longitudinal studies tracking student performance and interest in STEM over time could provide valuable insights into the factors that sustain engagement and lead to higher achievements in these fields. Studies could explore how STEM programs improve citizens' ability to discern credible scientific information from misinformation.

9.6 Providing students and citizens more opportunities to engage with competent and influential STEM educators and leaders

This objective emphasises the importance of interaction between learners at all levels and high-quality STEM educators and leaders. Such engagements could inspire students and citizens, sparking interest and perseverance in STEM fields. To support this goal, research should investigate the characteristics of effective STEM educators and leaders, including their pedagogical approaches, communication skills, and ability to connect with diverse audiences. Studies could also evaluate the impact of STEM professionals' mentorship programs, guest lectures, and workshops on students' attitudes towards STEM careers. Furthermore, research on the scalability and accessibility of these opportunities, especially in underserved areas, could inform policies to broaden the impact of influential STEM educators and leaders.

9.7 Tackling and narrowing the disparities in STEM talent and skills

Addressing the uneven distribution of STEM talent and skills across different demographics and regions is critical for ensuring equitable access to STEM education and careers. This goal calls for a comprehensive approach to identifying and reducing STEM readiness and achievement gaps. Research in this area should focus on the root causes of disparities, such as socioeconomic factors, educational inequities, gender, and cultural biases. Although much work has been done in targeting gaps (e.g., EC, 2021; Borgonovi et al., 2017), there is relatively little research on bridging them. Studies could examine the effectiveness of targeted interventions in closing these gaps, such as scholarships, tutoring, and STEM-focused programs.

9.8 Raising community consciousness and encouraging backing for STEM projects

Increasing public support and awareness of STEM initiatives is vital for their success and sustainability. This goal involves promoting the value of STEM education and projects to the broader community, highlighting their importance for economic development, innovation, and societal well-being. Research supporting this goal should explore strategies for effectively communicating the benefits of STEM to the public. This could include studies on the impact of public science events, media campaigns, and community-based STEM programs on public perceptions of STEM. Additionally, research on partnerships between schools, universities, businesses, and government agencies could provide models for collaborative efforts to enhance community support for STEM initiatives.

10 Resources that can help analyse STEM outcomes in Europe

Below, we present selected resources to address the multiplicity of STEM outcomes while enabling cross-country comparisons within the European Union. While none of the available studies is exclusively focused on STEM, many contain useful elements that can be valuable in analyses, depending on the questions posed. In this review, we limit ourselves to studies that measure cognitive abilities. It's important to emphasise that there are also numerous surveys that inquire, in a narrower or broader sense, about attitudes towards science (such as Eurobarometer, Gallup, and the Wellcome Trust), which are also crucial components of building a comprehensive understanding of STEM. However, without information on the individual skills, these appear incomplete and have limited utility. Similarly, declarative studies from Eurostat on skills or information about credentials in Eurostat's education and training statistics fall into this category.

10.1 Programme for International Student Assessment (PISA)

PISA is an international study coordinated by the Organisation for Economic Co-operation and Development (OECD) that commenced in 2000. Its primary objective is to evaluate more than 80 education systems worldwide by testing the skills and knowledge of 15-year-old students in participating countries and economies. Every three years, PISA evaluates students' skills in reading, mathematics, and science applied to real-life situations instead of being more curriculum-based than other studies. PISA emphasises a different subject in each cycle, starting with reading in 2000, shifting to mathematics in 2003, science in 2006, and back to reading in 2009. The focus continued to rotate, spotlighting mathematics again in 2012, science in 2015, and reading in 2018. The assessment planned for 2021 was delayed to 2022 due to the pandemic, with a renewed focus on mathematics.

Like any empirical study, especially a large comparative assessment of skills, PISA has limitations, and some aspects of the study have faced criticism over the years. Mainly, PISA has been criticized for adopting flawed theoretical assumptions that may not fully capture the complexities of education systems (Sjøberg & Jenkins, 2022). Critics argue that the assessment's theoretical framework might not be universally applicable across diverse cultural and educational contexts, leading to concerns about the validity of cross-national comparisons. Additionally, methodological issues have been highlighted, such as biases in sample selection or statistical models that may oversimplify or misrepresent the educational realities in different countries (Caro & Kyriakides, 2019). Measurement challenges have also been identified, particularly regarding the tools used to assess student performance and how accurately they reflect students' abilities across diverse contexts (Pokropek et al., 2022). Despite these criticisms, PISA provides a comprehensive approach to evaluating student skills and knowledge across more than 80 countries, offering invaluable data that can inform educational research and policymaking globally. The study's findings are widely recognized and used by hundreds of researchers worldwide who analyse PISA data and publish their discoveries, confirming its value and relevance in understanding education systems.

Table 3. Summary of PISA core domains

Mathematics	Mathematics is defined as students' capacity to reason mathematically and to formulate, employ and interpret mathematics to solve problems in a variety of real-world contexts. It includes concepts, procedures, facts and tools to describe, explain and predict phenomena. It helps individuals make well-founded judgements and decisions, and become constructive, engaged and reflective 21st-century citizens.
Reading	Reading is defined as students' capacity to understand, use, evaluate, reflect on and engage with texts in order to achieve one's goals, develop one's knowledge and potential, and participate in society.
Science	Science literacy is defined as students' ability to engage with science-related issues, and with the ideas of science, as a reflective citizen. A scientifically literate person is willing to engage in reasoned discourse about science and technology, which requires the competencies to explain phenomena scientifically, evaluate and design scientific enquiry, and interpret data and evidence scientifically.

Source: OECD (2023).

The PISA core domains are summarised in Table 3, which demonstrates a close alignment between PISA's assessment and the OECD analytical framework (OECD, 2023), as well as the STEM subjects described in Table 1 of this report, based on the Key Competences for Lifelong Learning (EU, 2018). Additionally, Table 3 provides a general definition of STEM subjects that emphasises an interdisciplinary approach and the real-world relevance of STEM subjects, highlighting their critical role in fostering analytical and problem-solving skills. At least conceptually, PISA is a valuable tool for evaluating and enhancing educational outcomes in STEM education.

It is important to emphasize that the PISA framework is not aligned with national curricula, as it focuses on assessing more general, cross-disciplinary skills, rather than curriculum-specific knowledge. PISA measures students' ability to apply their knowledge in real-life situations, emphasizing problem-solving, critical thinking, and adapting to new challenges. This approach contrasts with assessments directly tied to a particular country's curriculum, which typically focus on content mastery.

PISA also explores elements of 21st-century competencies by introducing innovative domains during each assessment cycle starting from 2012. In the 2012 cycle, PISA introduced an assessment focused on creative problem-solving. This evaluation aimed to gauge students' ability to understand and tackle problems where the solution is unclear, assessing their readiness to engage with complex situations to fulfil their roles as constructive and reflective citizens.

Moving forward to 2015, PISA shifted its focus to collaborative problem-solving, evaluating the capacity of students to work effectively as team members in problem-solving scenarios, reflecting the growing importance of teamwork in an interconnected global landscape. The assessment of collaborative problem-solving required students to interact with a simulated computer environment to solve problems, which were designed to represent different profiles of team members and react to students' responses following a script in a virtual chat. The assessment included several collaborative problem-solving tasks (group decision-making, coordination, and production) to elicit different problem-solving behaviours and interactions between the students and computer simulations (OECD, 2017).

The 2018 cycle introduced an assessment of "global competences", which measures skills for cultural awareness, respectful interaction in diverse societies, effective communication in

multicultural settings, critical engagement with digital media, and active participation in addressing global challenges. The PISA 2018 global competence assessment relied on a test focused on cognitive aspects, including knowledge and cognitive skills, and a set of questionnaire items collecting self-reported information from students, parents, teachers, and school principals (OECD, 2018).

Most recently, in 2022, PISA explored the domain of creative thinking. This assessment examined students' ability to produce varied and novel ideas, refine and improve these ideas, and engage in open-ended communication and problem-solving across different settings. The PISA 2022 creative thinking assessment features new methods, including interactive visual tasks for students to create images instead of writing or selecting answers. It uses open-ended questions with multiple correct answers, requiring advanced scoring techniques (OECD 2019).

PISA extends beyond assessing academic skills in reading, mathematics, and science. It also gathers comprehensive data from students, teachers, principals, and parents on various aspects that could influence educational outcomes. This includes questions on the learning environment, teaching practices, resources available at home and school, and students' attitudes towards learning. Such rich, multidimensional data enables a deeper analysis of the factors affecting student performance and provides valuable insights for developing effective educational policies and practices.

While the cognitive assessment and the student questionnaire are obligatory components for countries participating in PISA, other elements such as teacher and parental questionnaires and additional options such as an in-depth ICT questionnaire or financial literacy assessment (not discussed later because of the limited importance for STEM) are not mandatory. Countries can choose whether to include these supplementary components, allowing them to tailor the assessment to their interests and needs. Below, we provide a short overview of what could be found in PISA noncognitive data.

10.1.1 PISA Student Questionnaire

Over the years, the PISA Student Questionnaire has assessed various factors concerning students' backgrounds, attitudes towards learning, educational experiences, and environmental contexts. Specifically, it covers:

- **Demographic information:** Questions about the student's grade, birth date, gender, and educational program.
- **Home environment:** Details about the physical home environment, including access to a room of one's own, computers, educational software, internet access, and ownership of various items like books, cars, musical instruments, and works of art. It also probes the digital landscape at home, including the number of digital devices.
- **School experience:** Questions focus on the student's length of enrolment at their current school, experiences of repeating grades, absenteeism, and their reasons, alongside their daily routines before and after school.
- **Educational aspirations and perceptions:** The questionnaire delves into students' further educational and career expectations, satisfaction with life, weekly school schedules, and confidence in handling various academic tasks, particularly in mathematics. It explores

their engagement in the classroom, perceptions of teacher support, and participation in group work and discussions.

- **Education:** In each cycle of PISA, a different subject area (math, science or reading) is explored more in-depth. The questionnaire captures students' confidence, anxiety levels, and familiarity with concepts across these subjects. Additionally, it assesses how frequently students encounter specific tasks in reading, mathematics, or science, and their perceptions of the quality of instruction in these areas. The questionnaire also explores students' engagement in supplementary instruction beyond the standard curriculum for a holistic view of their educational experience.
- **Social and emotional well-being:** The questionnaire assesses students' social behaviours, empathy, trust in others, emotional regulation, and bullying experiences. It also measures their perspectives on safety at school, relationships with teachers and peers, and personal attitudes toward learning, curiosity, persistence, and cooperation.
- **Digital use:** Questions about using digital devices for learning and leisure, including managing notifications and feelings of anxiety when away from digital devices.
- **Learning behaviours and attitudes:** It assesses learning strategies, effort in homework, participation in lessons and attitudes towards mathematics, reading and science subjects.

10.1.2 PISA School Questionnaires

PISA also administered School Questionnaires to all principals participating in the study. The questionnaire covers a broad range of topics aimed at understanding the context in which students learn:

- **School Background Information:** General information about the school, including the community type it is located in (e.g., village, town, city), whether it is public or private, and its funding sources.
- **School Management:** Administrative aspects, such as the impact of various issues on the school's capacity to provide instructions, including staff shortages and inadequacies, educational materials, and physical infrastructure.
- **Teaching Staff:** Inquiries about the composition of the teaching staff, their qualifications, and the extent to which they have participated in professional development programs.
- **Assessment and Evaluation:** The questionnaire asks about using student assessments for various purposes within the school, such as guiding learning, informing parents, making decisions about student retention or promotion, and evaluating teachers' effectiveness.
- **Targeted Groups:** It explores the school's policies and practices for supporting students with different needs, including career guidance availability and policies for students whose mother tongue is not the test language.
- **School Climate:** Principals are asked about the extent to which certain phenomena hinder student learning, including truancy, lack of respect for teachers, bullying, among others.

The student and school questionnaires are administered by all participating countries, while additional teacher, parental, and detailed ICT questionnaires are voluntarily administered by participating countries.

PISA's Teacher Questionnaire is designed to collect information on various aspects of teaching and the school environment. It is structured to gather data on the following key areas:

- **Background information:** Collects demographic information about the teachers, such as age, gender, and country of birth.
- **Education and professional development:** Inquires about teachers' highest level of education, types of degrees obtained, and participation in professional development activities.
- **Teaching practices:** Questions cover topics like the use of technology in the classroom, student assessment methods, collaboration with colleagues, and teaching practices.
- **Classroom and school environment:** Includes questions on classroom management, student diversity, instructional resources, and teacher autonomy in various aspects of their job.
- **Teacher beliefs and attitudes:** Ask teachers for their opinions on the importance of creativity, job satisfaction, and views on teaching and learning.
- **Well-being and stress:** Queries about teachers' well-being, experiences of stress, and physical symptoms related to stress.

10.1.3 PISA Parent Questionnaire

Parent Questionnaire for PISA is designed to gather information from parents or guardians about various aspects related to their child's education, including:

- **Family and Student Information:** Questions about the student's home environment, languages spoken at home, and the number of books and digital devices in the home.
- **School Engagement and Activities:** Inquires about parents' involvement in school activities and reasons for choosing the current school.
- **Educational Pathway and Expectations:** Ask parents about their expectations for their child's educational attainment, participation in early childhood education, additional instruction during primary education, and reasons for attending early childhood education and care arrangements.
- **Expenditure on Education:** Questions about the amount paid to educational providers for services in the last twelve months.
- **Household Income:** Inquires about the annual household income to understand the socioeconomic context of the student's family.

10.1.4 PISA ICT Familiarity Questionnaire

Finally, PISA has an optional ICT Familiarity Questionnaire since 2018, intended for students to assess their familiarity and engagement with various digital devices and the internet. This questionnaire covers several aspects, including:

- **Availability and use of digital devices:** Queries about specific devices at home and school, such as desktop computers, laptops, tablets, internet connections, and more. It also asks about the age at which students first used a digital device and accessed the internet.
- **Internet usage:** Questions about the frequency and duration of internet use at school, home during weekdays, and on weekends.
- **Educational use of digital devices:** Inquires about using digital devices for schoolwork inside and outside the classroom, including activities such as homework, research, and communication with teachers and students.
- **Digital activities:** Ask how often students engage in various digital activities outside of school, such as playing games, using email, participating in social networks, browsing the internet for fun, and more.
- **Self-efficacy and attitudes towards digital devices:** Designed to gauge students' confidence in using digital devices and solving related problems. They also aim to gauge their attitudes toward digital media, including whether they like discovering new devices or applications and how they feel when internet access is unavailable.
- **Learning and problem-solving with digital devices:** Seeks information on students' approaches to installing software, solving device problems, choosing applications, and their preferences for learning about and discussing digital devices with friends.
- **News consumption habits:** Queries about students' habits in consuming news, whether they follow it, and their preferences for digital devices versus traditional paper formats.

For Europe, PISA serves as the wealthiest data source on STEM skills, although it does not cover all countries in all time points. Table 4 presents a comprehensive summary of the last three cycles of the PISA assessment, including the optional components selected by European Union (EU) countries.

Notably, PISA also includes measures for well-being and financial literacy, although these areas are not the report's primary focus and are not indicated in the present table. We do not highlight these additional modules in the tables, as they are not strictly related to definitions of STEM education. In the case of the wellbeing module, only a small number of EU Member State countries participated in it (5 in 2018 and 4 in 2022).

Table 4. Summary of PISA assessment, including optional components for EU countries

Country	Main study			Innovative domains			ICT questionn.			Teacher questionn.			Parental questionn.		
	2015	2018	2022	CP	GC	CT	2015	2018	2022	2015	2018	2022	2015	2018	2022
Austria	✓	✓	✓	✓	✓		✓	✓	✓						
Belgium	✓	✓	✓	✓		✓	✓	✓	✓				✓	✓	✓
Bulgaria	✓	✓	✓	✓	✓	✓	✓	✓	✓						
Croatia	✓	✓	✓	✓	✓	✓	✓	✓	✓					✓	✓
Cyprus	✓	✓	✓	✓											
Czechia	✓	✓	✓	✓		✓	✓	✓	✓	✓					
Denmark	✓	✓	✓	✓		✓	✓	✓	✓						
Estonia	✓	✓	✓	✓	✓	✓	✓	✓	✓						
Finland	✓	✓	✓	✓		✓	✓	✓	✓						
France	✓	✓	✓	✓	✓	✓	✓	✓					✓		
Germany	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓
Greece	✓	✓	✓	✓	✓	✓	✓	✓	✓						
Hungary	✓	✓	✓	✓	✓	✓	✓	✓	✓						
Ireland	✓	✓	✓	✓	✓		✓	✓	✓				✓	✓	✓
Italy	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓
Latvia	✓	✓	✓	✓	✓	✓	✓	✓	✓						✓
Lithuania	✓	✓	✓	✓	✓	✓	✓	✓	✓						
Luxembourg	✓	✓		✓			✓	✓					✓	✓	
Malta	✓	✓	✓		✓	✓		✓	✓				✓	✓	
Netherlands	✓	✓	✓	✓		✓	✓								
Poland	✓	✓	✓	✓	✓	✓	✓	✓	✓						
Portugal	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓
Romania	✓	✓	✓		✓	✓			✓						
Slovakia	✓	✓	✓	✓	✓	✓	✓	✓	✓						
Slovenia	✓	✓	✓	✓	✓	✓	✓	✓	✓						
Spain	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Sweden	✓	✓	✓	✓			✓	✓	✓						

Source: Own elaboration.

Note: ✓: present in the assessment; CP: collaborative problem solving; GC: global competence; CT: creative thinking.

10.2 Trends in International Mathematics and Science Study (TIMSS)

The Trends in International Mathematics and Science Study (TIMSS) is an international assessment conducted by the International Association for the Evaluation of Educational Achievement (IEA). It evaluates fourth- and eighth-grade students' mathematics and science knowledge and skills. TIMSS aims to provide comparative data to inform educational policies and practices, improving teaching and learning in mathematics and science with more than 70 education systems participating worldwide. Initiated in 1995 and conducted every four years, the study allows participating countries to monitor their student's achievement over time and compare their education systems with those of other countries.

The essence of TIMSS is its curriculum-based assessment framework, which aligns closely with what students are taught in schools. This alignment ensures that TIMSS effectively measures students' mastery of content in these disciplines, providing a clear picture of how well educational systems deliver curriculum-based knowledge. The approach taken by TIMSS can be described as multidisciplinary, given its focus on distinct academic domains, without necessarily integrating them into a broader context (Mullis and Martin, 2017). The summary of TIMSS core domains is presented in Table 5.

Table 5. Summary of TIMSS core domains

Mathematics	Fourth-grade assessment in three content domains: number, measurement and geometry, and data; eighth-grade assessment in four content domains: number, algebra, geometry, and data and probability.
Science	Fourth-grade assessment in three content domains: life science, physical science, and Earth science; eighth-grade assessment in four content domains: biology, chemistry, physics, and Earth science. The proportion of each assessment devoted to the content domains differed to reflect curricular emphases in each grade.

Source: Mullis et al. (2022).

When comparing the core domain descriptions, significant differences between PISA and TIMSS become apparent. TIMSS focuses on subject-specific knowledge and skills, examining students' understanding and abilities within specific academic disciplines. In contrast, PISA emphasises general competencies across various domains, placing a stronger emphasis on overarching problem-solving skills within its frameworks. Recent cycles of TIMSS have shown a gradual shift towards a more PISA-like perspective, however. This evolution suggests an increasing recognition of the importance of general problem-solving abilities alongside traditional subject knowledge. The latest reports from TIMSS indicate a move in this direction:

> *Previous TIMSS Mathematics frameworks have not been clear about the degree of emphasis that should be placed on solving problems in context (…) The TIMSS 2023 Mathematics Framework specifies that approximately 85 percent of the items covering the topics in each content domain should be situated in a problem solving context. This is consistent with other aspects of the framework, and clarifies that problem solving is an overarching goal of TIMSS Mathematics, and not associated only with particular topics (Mullis et al., 2022: 6).*

This shift is also evidenced by introducing Problem Solving and Inquiry Tasks (PSIs). The initiative, which commenced with TIMSS 2019, aimed to develop and administer longer, scenario-based PSIs in mathematics and science assessments. This approach marks a significant evolution in the assessment strategy, bridging the gap between traditional subject-focused queries and more comprehensive, real-world problem-solving scenarios. The objective was not to introduce new concepts of problem-solving and inquiry but rather to gather data that would contribute to broadening the scope of the TIMSS assessment. The PSI tasks offer visually appealing, interactive scenarios that engage students dynamically. These tasks guide students through a sequence of steps towards achieving a specific solution or goal, accommodating adaptive and responsive interaction. Student responses are captured through a blend of constructed response items, alongside with various innovative methods such as number pads, drag-and-drop capabilities, graphing tools, and free drawing options (Mullis et al., 2021).

TIMSS also includes advanced components designed to measure advanced mathematics and physics competencies for students in their final year of secondary school. The Advanced Mathematics Assessment evaluates knowledge in algebra, calculus, and geometry and assesses mathematical thinking in knowing, applying, and reasoning, with each domain contributing differently to the overall score. The Physics Assessment mirrors this structure, focusing on mechanics and thermodynamics, electricity and magnetism, wave phenomena and atomic/nuclear physics. It evaluates scientific thinking in the same cognitive domains, with varying contributions to the total score. These components aim to provide a thorough evaluation of students' advanced skills in these subjects.

Like PISA, TIMSS also collects contextual information to enhance understanding of educational outcomes. TIMSS gathers data on the contexts for learning by distributing questionnaires to be completed by students and their parents, teachers, and school principals.

10.2.1 TIMSS Student Questionnaire

The TIMSS Student Questionnaire evaluates diverse aspects of students' backgrounds, educational settings, and views on learning and school life. Grade 4th and Grade 8th differ in detail as they are adapted to age, but both explore similar topics:

- **Demographic and background information:** Questions inquire about students' gender, ethnicity, birth date, and linguistic background, aiming to understand the student's identity and cultural context.

- **Home environment and resources:** The questionnaire gathers information on the availability of educational and digital resources at home, such as books, computers, internet access, and personal study spaces.

- **School experiences:** Queries are made regarding students' participation in extracurricular activities, bullying experiences, and overall feelings towards school.

- **Attitudes towards and perceptions of mathematics and science:** The questionnaire delves into students' confidence in and attitudes toward mathematics and science, including their interest in these subjects, self-assessment of abilities, and perceptions of classroom dynamics and teacher effectiveness.

- **Learning in mathematics and science:** Questions focus on the nature of instruction and student participation in mathematics and science classes, including the frequency of independent problem-solving and conducting experiments. This section evaluates educational practices and students' active involvement in these subjects.

- **Self-efficacy and school environment:** The questionnaire probes students' self-efficacy beliefs regarding mathematics and science and their perceptions of the school environment, including classroom behaviour and the disciplinary climate. It also explores students' views on the fairness and supportiveness of their teachers.

The 8th Grade TIMSS Student Questionnaire, tailored for older students, focuses on advanced educational and career planning topics, emphasising future aspirations. It explores the increased

use of digital resources for schoolwork, including internet access, for assignments and collaboration. The questionnaire also addresses homework frequency and duration.

10.2.2 TIMSS Teacher Questionnaire

TIMSS ensures that teacher questionnaires are filled out in every country, unlike in PISA, where they are optional. Additionally, TIMSS employs a distinct sampling strategy by selecting entire classes rather than a random sample from the school. This method allows for a direct matching between teacher responses and student responses. Similar to the student questionnaire, the teacher questionnaires are tailored to the specific level of instruction but generally address similar topics:

- **Teacher background and education:** Questions regarding teachers' years of experience, gender, age, highest level of education completed, and main area(s) of study during their education.
- **School environment and academic success:** Teachers' perceptions of their school's emphasis on academic success, including understanding of curricular goals, success in curriculum implementation, expectations for student achievement, parental involvement, and student motivation and respect for academic excellence.
- **Teacher attitudes and challenges:** Teachers' satisfaction with their profession, the meaning and purpose they find in their work, and challenges they face, such as class size, workload, administrative tasks, and the pressure from various stakeholders.
- **Teaching practices for the TIMSS class:** Teaching practices employed include integrating real-life examples into lessons, encouraging classroom discussions, and adapting teaching strategies to overcome students' language understanding difficulties.
- **Mathematics and science instruction:** Detailed questions about the amount of time spent teaching these subjects, instructional methods, use of calculators and computers, topics covered, homework, and assessment strategies to gauge instructional approaches and content emphasis.
- **Use of technology in teaching:** Questions about the availability and use of computers and tablets for teaching mathematics and science, aiming to understand the role of technology in contemporary classroom instruction.
- **Content and curriculum:** Insight into the mathematics and science topics taught to the class provides a view of the curriculum coverage and instructional focus within these core subjects.
- **Professional development:** Teachers' participation in professional development activities related to mathematics and science content, pedagogy, curriculum, technology integration, assessment strategies, and addressing individual students' needs, reflecting on the support and resources available for teacher growth.
- **Assessment practices:** The importance placed on various assessment strategies in mathematics and science and the frequency of digital assessments to understand the evaluative approaches used to measure student learning.

10.2.3 TIMSS School Questionnaire

TIMSS administers school questionnaires designed for school principals and department heads to provide information about their schools. Similar to the student and teacher questionnaires, the school questionnaires are tailored to the specific level of instruction but generally address similar topics:

- **School enrolment and characteristics:** Questions about the total student enrolment, the percentage of students from economically disadvantaged or affluent homes, and the native language of students.
- **Instructional time:** Inquiry about the number of days per year the school is open for instruction, total instructional time in a typical day, and the number of days the school is open for instruction in a week.
- **Resources and technology:** Questions on the availability of a school library, the number of computers for fourth-grade students, science laboratory access, and whether the school provides digital learning resources or uses an online learning management system.
- **General school resources and instruction:** Queries about the adequacy of instructional materials, technological resources, resources for students with disabilities, and resources specific to mathematics and science instruction.
- **School discipline and safety:** Assessment of problems such as absenteeism, classroom disturbance, cheating, vandalism, and intimidation among students.
- **School emphasis on academic success:** Evaluation of the school environment, including teachers' understanding of curricular goals, success in implementing the curriculum, expectations for student achievement, and parental involvement.
- **School readiness:** Questions about the readiness of students entering the first grade, including their ability to recognise letters, read and write words, count, and perform simple arithmetic.
- **Principal experience and education:** Information about the principal's total years of experience, highest level of formal education, and qualifications or credentials in educational leadership.

10.2.4 Other TIMSS Questionnaires

TIMSS also includes a Home Questionnaire, or Early Learning Survey, filled out by parents or guardians of fourth graders. It gathers data on home learning resources, parental education and employment, views on the child's school, pre-primary education, and early literacy and numeracy activities and skills.

Finally, TIMSS features Curriculum Questionnaires completed by each country's National Research Coordinator, focusing on national curriculum policies, education systems, and the structure and content of math and science curricula. These tools offer insights into the educational context and factors influencing student achievement.

Table 6 summarizes the TIMSS assessment results for EU countries. It highlights students' performance in mathematics and science at different educational stages, including those enrolled in

advanced mathematics and physics programs in secondary school through the TIMSS advanced assessment.

Table 6. Summary of TIMSS assessment for EU countries

Country	1995			1999	2003		2007		2008	2011		2015			2019		2023	
	4G	8G	LS	8G	4G	8G	4G	8G	LS	4G	8G	4G	8G	LS	4G	8G	4G	8G
Austria	✓	✓	✓				✓			✓					✓			✓
Belgium		✓		✓	✓	✓				✓		✓			✓		✓	
Bulgaria		✓		✓		✓		✓				✓			✓		✓	
Croatia										✓		✓			✓			
Cyprus	✓	✓	✓	✓	✓	✓		✓				✓			✓	✓	✓	✓
Czechia	✓	✓	✓	✓			✓	✓		✓		✓			✓		✓	✓
Denmark		✓	✓				✓			✓		✓			✓		✓	
Estonia						✓												
Finland				✓						✓	✓	✓			✓	✓	✓	✓
France		✓	✓									✓		✓	✓	✓	✓	✓
Germany		✓	✓				✓			✓		✓			✓		✓	
Greece	✓	✓	✓															
Hungary	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓
Ireland	✓	✓								✓		✓	✓		✓	✓	✓	✓
Italy	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Latvia	✓	✓	✓	✓	✓	✓	✓								✓		✓	
Lithuania		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓
Luxembourg																		
Malta								✓		✓			✓		✓			✓
Netherlands	✓	✓		✓	✓	✓	✓		✓	✓		✓			✓		✓	
Poland										✓		✓			✓		✓	
Portugal	✓	✓	✓							✓		✓		✓	✓	✓	✓	✓
Romania		✓		✓		✓		✓		✓	✓					✓	✓	✓
Slovakia		✓		✓		✓	✓			✓		✓			✓		✓	
Slovenia	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	
Spain		✓		✓						✓		✓			✓		✓	
Sweden		✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Source: Own elaboration.

Note: 4G: 4th grade TIMSS; 8G: 8th grade TIMSS; LS: last-year secondary school TIMSS advanced.

10.3 Programme for the International Assessment of Adult Competencies (PIAAC)

The Programme for the International Assessment of Adult Competencies (PIAAC) is a global initiative led by the Organisation for Economic Co-operation and Development (OECD) to evaluate the skills and competencies of the adult population. It is the only assessment that comparatively evaluates adults' cognitive abilities in multiple countries. Similar to how PISA assesses the capabilities of 15-year-old students, PIAAC aims to understand the proficiency of adults aged 16-65 in key areas such as literacy, numeracy, and problem-solving in technology-rich environments. A short description of PIAAC domains is provided in Table 7.

Table 7. Summary of PIAAC domains

Literacy	Literacy is understanding, evaluating, using and engaging with written texts to participate in society, to achieve one's goals, and to develop one's knowledge and potential.
Numeracy	The ability to access, use, interpret, and communicate mathematical information and ideas, to engage in and manage mathematical demands of a range of situations in adult life.
Problem solving in technology-rich environments	Problem solving in technology-rich environments involves using digital technology, communication tools and networks to acquire and evaluate information, communicate with others, and perform practical tasks. PIAAC problem-solving survey focus on the abilities to solve problems for personal, work and civic purposes by setting up appropriate goals and plans, accessing and making use of information through computers and computer networks.

Source: PIAAC, 2009a, 2009b, 2009c.

The PISA and PIAAC domains exhibit remarkable similarities. Their close alignment enables some scholars to argue that these assessments measure the same underlying constructs (Borgonovi et. al., 2017). Attempts have been made to link these assessments by placing them on a common scale (Pokropek & Borgonovi, 2020).

PIAAC is designed to be carried out at least every ten years. Preliminary work on PIAAC started in 2008/09 and its inaugural round took place in 2011. The survey was administered twice more until 2017 using the same set of survey instruments. Across these initial rounds, known as Cycle I (2011-18), 39 countries participated in PIAAC. Cycle II started in 2022-2023 featuring updated survey instruments with 31 countries participating in the first wave of data collection.

PIAAC's background questionnaire gathers detailed information on respondents' demographics, educational and training history, employment status, and skill application in home and work environments. The questionnaire also assesses skills-related social outcomes, such as social participation, civic engagement, and community involvement.

Table 8. Summary of PIAAC assessment for EU countries

Country	Cycle 1			Cycle 2
	Round 1 2011	Round 2 2014	Round 3 2018	Round 1 2022/23
Austria	✓			✓
Belgium	✓			✓
Bulgaria				
Croatia				✓
Cyprus	✓			
Czechia	✓			✓
Denmark	✓			✓
Estonia	✓			✓
Finland	✓			✓
France	✓			✓
Germany	✓			✓
Greece		✓		
Hungary			✓	✓
Ireland	✓			✓
Italy	✓			✓
Latvia				✓
Lithuania		✓		✓
Luxembourg				
Malta				
Netherlands	✓			✓
Poland	✓			✓
Portugal				✓
Romania				
Slovakia	✓			✓
Slovenia		✓		
Spain	✓			✓
Sweden	✓		✓	✓

Source: Own elaboration.
Note: A second round of data collection for cycle 2 is planned is expected to take place in 2025-20292.

10.4 International Computer and Information Literacy Study (ICILS)

The International Computer and Information Literacy Study (ICILS), conducted by the International Association for the Evaluation of Educational Achievement (IEA), evaluates 8th-grade students' computer and information literacy (CIL) abilities. It is the only large international study which assesses technology elements that could be understood as parts of the STEM concept. This global study assesses how well students can use information and communications technology (ICT) to research, create, and communicate across home, school, workplace, and community environments. ICILS categorises skills into four levels: basic software knowledge, use of computers for information

[2] See https://www.oecd.org/en/about/programmes/piaac.html#data; last access on 29 August 2024.

sourcing, adequate ICT skills for information gathering and utilisation, and critical online information search skills (Fraillon et al., 2014).

The ICILS assessment framework is revised for each cycle of the assessment. In its first cycle in 2013, student's computer and information literacy (CIL) was delineated into two key strands reflecting the scope of skills and knowledge assessed. Strand 1 emphasised understanding and managing digital information, including computer use, accessing, evaluating, and organising information. Strand 2 focused on the creation and sharing of digital content. In the second cycle, ICILS 2018 aimed to refine the CIL assessment adopting a framework with two key areas of proficiency in information and communication technologies. The first, computer and information literacy (CIL), concentrates on the abilities related to using computers, sourcing information, producing content, and digital communication. The second, computational thinking (CT), concerns the ability to define problems clearly and devise effective solutions. In the third and most recent cycle in 2023, while the content for CT assessment remained consistent, the test structure was updated to represent the integrated process of problem-solving core to CT more accurately.

Table 9. Summary of ICLS 2023 domains

Computer and Information Literacy (CIL)	**Understanding Computer Use:** Covers the basics of how computers work and how to interact with them, focusing on foundational knowledge and the conventions of computer use. **Gathering Information:** Involves finding, evaluating, and managing digital information, highlighting skills in accessing information and organizing it effectively. **Producing Information:** Focuses on creating digital content, emphasizing transforming information for clarity and generating new, original information products. **Digital Communication:** Pertains to sharing information digitally, considering social, legal, and ethical aspects of online communication, and promoting safe and secure information use.
Computational Thinking (CT)	**Conceptualizing Problems:** This involves understanding digital systems, formulating and analysing problems to break them down into parts, and collecting and representing relevant data for effective judgment. **Operationalizing Solutions:** Addresses creating, implementing, and evaluating computer-based solutions, focusing on planning and evaluating solutions and developing algorithms, programs, and interfaces for real-world applications.

Source: Fraillon & Rožman (2024).

A separate questionnaire is provided to select teachers across all subjects in the target grade. This questionnaire collects information on teachers' backgrounds, use of ICT, and experiences with professional development related to ICT. It asks teachers to evaluate their confidence in integrating computers into their teaching practices, to detail the frequency and nature of specific ICT teaching activities, and to disclose which ICT tools they employ. Additionally, it inquires about the extent to which they incorporate computer and information literacy (CIL) and computational thinking (CT) into their teaching, and it gauges their perspectives on using computers in educational settings.

Finally, a questionnaire for school principals from participating schools aims to gather details on school characteristics, policies and approaches towards using ICT in teaching and learning. It also examines aspects related to the management of ICT resources within the school and explores the leadership's vision and strategies for implementing technology use in education.

Table 10. Summary of ICILS assessment for EU countries

Country	2013	2018	2023
Austria			✓
Belgium			✓
Bulgaria			
Croatia	✓		✓
Cyprus			✓
Czechia	✓		✓
Denmark	✓	✓	✓
Estonia			
Finland		✓	✓
France		✓	✓
Germany	✓	✓	✓
Greece			✓
Hungary			✓
Ireland			
Italy			✓
Latvia			✓
Lithuania	✓		
Luxembourg		✓	✓
Malta			✓
Netherlands	✓		✓
Poland	✓		
Portugal		✓	✓
Romania			✓
Slovakia	✓		✓
Slovenia	✓		✓
Spain			✓
Sweden			✓

Source: Own elaboration.

Note: The launch of a public-use database and documentation for round 3 is scheduled for March 2025.

Conclusions

The traditional notion of STEM education encompassing the disciplines of science, technology, engineering, and mathematics originates from a pragmatic response to emerging workforce needs. In the 1990s, a new educational focus combining these disciplines motivated nations' technological advancement and competitiveness, and ever since, the concept behind STEM education and its variations has not stopped evolving.

The past few decades have seen fast-paced technological progress coupled with the rise of green and digital transitions. These factors have significantly influenced how we perceive STEM, pushing its boundaries beyond its traditional realms. Advocates of integrated STEM education argue that conventional education is misaligned with such a dynamic environment, primarily due to the static nature of traditional education models. Adapting to the new learning environments and job market needs would require broader, more flexible competencies, relying on interdisciplinary knowledge. Therefore, the integrated STEM approach defends an educational framework combining disciplinary integration and emphasises the development of 21st-century skills (also known as transversal skills) such as adaptability, problem-solving, and creativity.

The integrated STEM education concept overlaps with its STEAM extension, which includes the arts disciplines. The first STEAM was coined in 2006 to create a more cohesive curriculum, but some scholars suggest that it is also a strategic approach to fostering 21st-century skills in teaching and learning practices. However, the intricacies of this conceptualisation remain far from clear. First, the interpretation of arts within this framework can be associated with multiple definitions, either visual arts only, including performing arts and crafts, or encompassing liberal arts and humanities. In practice, it is possible to assume that the "A" in STEAM can emphasise either "Attitudes" or "Additional skills" to STEM competencies (Zeidler, 2016). Despite being a pathway towards equitable learning, scholars agree that the conceptualisation and usage of STEAM are ambivalent and weekly theorised, highlighting the need for further empirical validation.

Despite the common understanding that integrated STEM and STEAM approaches are key to real-world challenges, there is a lack of common understanding behind their conceptualisation. The definition of STEM proficiency in education is complex and multi-level, ranging from broad formulations such as "STEM literacy" and "STEM competencies" to detailed aspects of STEM knowledge, skills, and attitudes. This report presented various definitions of "STEM literacy" adopted worldwide, notably from the National Science Foundation and the Washington STEM Study Group. These are usually centred around the awareness of STEM disciplines and familiarity with each concept, besides the capacity to utilise this knowledge to address complex, real-world problems. The Council of the European Union (2018) has proposed a broad definition of "STEM competencies", encompassing the necessary (integrated) knowledge, skills, and attitudes to empower individuals. In parallel, defining 21st-century skills is also challenging, and proposals range from focusing on the "four C's", i.e., critical thinking, communication, collaboration, and creativity (National Education Association, 2012), or the categorisation into cognitive, intrapersonal, and interpersonal domains (National Research Council, 2012).

The lack of consensus on conceptualizing integrated STEM and STEAM approaches complicates efforts to analyse educational outcomes. From an educational perspective, this ambiguity poses challenges for curriculum design, teaching methodologies, and the evaluation of student progress. Without a unified understanding of a truly integrated STEM or STEAM program, educators may implement differing practices, leading to inconsistencies in how students acquire essential skills.

This fragmentation can affect students' preparedness for the workforce, as educational programs may need to fully align with the skills required in modern industries. Integrated STEM and STEAM approaches seem to be particularly valuable. However, without a standardized approach, it becomes difficult to measure the effectiveness of these methods in promoting such competencies.

Furthermore, uncertainty about what integration should look like also complicates teacher professional development, making it harder to equip them with the tools and strategies necessary to implement effective integrated learning. Consequently, the potential of integrated STEM/STEAM education to contribute to workforce readiness may be undermined by inconsistent delivery and unclear expectations.

While integrated STEM/STEAM education has many potential benefits, it has little empirical base. One of the main and most concerning findings of this literature review is the scarcity of research on the effectiveness of STEM education. The lack of empirical evidence and well-designed studies on STEM education and its effectiveness, particularly in the European context, is a significant gap. This underscores the urgent need for more research and evidence-based practices in STEM education. According to some studies (Li et al. 2020), about 75% of the articles on STEM education come from the USA, and very little evidence stems from the European Union (EU27). An even more intriguing and surprising discovery is that most articles, which account for almost half of the publications, are not research articles but primarily discussions or summaries that do not expand our scientific knowledge around the topic (Li et al. 2020). The remaining few sources, with their own limitations, give no clear consensus on the best practices for integrated STEM education and its effect on students' outcomes. One of the most important factors for developing STEM education is increasing the number of well-designed studies on the effectiveness of STEM and STEAM, particularly in the European context, where there is a significant lack of such research. New studies incorporating experimental and longitudinal designs could contribute to a better understanding of STEAM education. However, it is essential to recognise that the costs and complexity of these studies are incredibly high, and therefore, adequate funding sources must be secured to support them.

In addition to investing in new research, another option is to make better use of existing data. This refers to large-scale assessments, which, while having their limitations, hold significant potential for studying STEM education from a comparative perspective. Since these studies are purely correlational, they cannot provide strong evidence about the effectiveness of different approaches. However, they are useful for monitoring certain aspects of STEM education and conducting preliminary research, as well as exploring hypotheses that could be tested in more targeted studies.

Large-scale assessment data enable cross-country comparisons of STEM-related competencies for European Union countries, such as the Programme for International Student Assessment (PISA), the Trends in International Mathematics and Science Study (TIMSS), the Programme for the International Assessment of Adult Competencies (PIAAC), and the International Computer and Information Literacy Study (ICILS). While none focuses exclusively on STEM, they are useful for analysing related learning outcomes.

PISA was launched by the OECD in 2000 to evaluate education systems by testing the skills and knowledge of 15-year-old students in more than 80 participating countries (not all EU27). It evaluates students' reading, mathematics, and science skills every three years, emphasising a different subject in each cycle. Since 2012, it also explores 21st-century skills, including creative and collaborative problem-solving, global competence, and creative thinking. Finally, PISA includes

student, teacher, school, and parent questionnaires to gather extra information related to children's and teacher's attitudes, amongst other things.

TIMSS was initiated by the International Association for the Evaluation of Educational Achievement (IEA) in 1995 to evaluate the knowledge and skills of fourth- and eighth-grade students in mathematics and science in more than 70 countries. In contrast with PISA, its curriculum-based assessment framework aligns closely with what students are taught in schools, providing a snapshot of how well educational systems deliver knowledge. In more recent cycles, TIMSS has increasingly recognised problem-solving abilities alongside knowledge from traditional disciplines. Similarly to PISA, TIMSS also collects contextual information to enhance the understanding of educational outcomes through student, teacher, school, and parent questionnaires.

The OECD launched PIAAC in 2011 to evaluate adults' (16-65) skills in participating countries at least every ten years. The assessment focuses on literacy, numeracy, and problem-solving in technology-rich environments. Background questionnaires gather information on respondents' demographics, educational and training history, employment status, and skills application in home and work environments. The questionnaire also assesses skills-related social outcomes, such as social participation, civic engagement, and community involvement.

Finally, IEA launched ICILS in 2013 to evaluate 8th-grade students' computer and information literacy (CIL) abilities. It is the only large international study which assesses technology elements that could be understood as parts of the STEM concept, categorised as basic software knowledge, use of computers for information sourcing, adequate ICT skills for information gathering and utilisation, and critical online information search skills. Similar to other assessments, ICILS also provide teacher and school questionnaires.

As the global economy continues to evolve and everyday life changes due to technological development, the necessity for STEM skills becomes more critical than ever. However, more clarity and consensus on what constitutes essential STEM competencies is needed to support efforts to prepare students effectively for future challenges. Addressing disparities in STEM talent distribution and increasing public support for STEM initiatives are crucial for equitable access to education and career opportunities. In addition, continued research into effective educational strategies and enhanced communication of STEM benefits to students and teachers is vital for these purposes.

References

Acemoglu, D. and Restrepo, P. (2019). *Automation and new tasks: How technology displaces and reinstates labor.* Journal of economic perspectives, *33*(2): 3-30.

Aguilera, D. and Ortiz-Revilla, J. (2021). *STEM vs. STEAM education and student creativity: A systematic literature review.* Education Sciences, 11(7), 331.

Avvisati, F. and Givord, P. (2023). *The learning gain over one school year among 15-year-olds: An international comparison based on PISA.* Labour Economics, 84, 102365.

Becker, K. and Kyungsuk, Park. (2011). *Integrative approaches among science, technology, engineering, and mathematics (STEM) subjects on students' learning: A meta-analysis.* Journal of STEM education: Innovations and research, 12.5 (2011).

Belbase, S., Mainali, B. R., Kasemsukpipat, W., Tairab, H., Gochoo, M. & Jarrah, A. (2022) *At the dawn of science, technology, engineering, arts, and mathematics (STEAM) education: prospects, priorities, processes, and problems*, International Journal of Mathematical Education in Science and Technology, 53:2919-2955.

Blazar, D. (2015). *Effective teaching in elementary mathematics: Identifying classroom practices that support student achievement.* Economics of Education Review, 48: 16-29.

Borgonovi, F., Pokropek, A., Keslair, F., Gauly, B., and Paccagnella, M. (2017). *Youth in transition: How do some of the cohorts participating in PISA fare in PIAAC?* OECD Education Working Papers No. 155, OECD Publishing, Paris, http://dx.doi.org/10.1787/51479ec2-en.

Brynjolfsson, E. and McAfee, A. (2014). *The second machine age: Work, progress, and prosperity in a time of brilliant technologies*. W. W. Norton & Company.

Caro, D. and Kyriakides, L. (2019). *Assessment design and quality of inferences in PISA: limitations and recommendations for improvement*, Assessment in Education: Principles, Policy & Practice, 26:4, 363-368, DOI: 10.1080/0969594X.2019.1645990.

Çetin, M. and Demircan, H. Ö. (2020). *Empowering technology and engineering for STEM education through programming robots: A systematic literature review.* Early Child Development and Care, 190(9): 1323-1335.

Cimer, A. (2007). *Effective teaching in science: A review of literature.* Journal of Turkish science education, 4(1): 20-44.

Collins, A. and Halverson, R. (2018). *Rethinking education in the age of technology: The digital revolution and schooling in America.* Teachers College Press.

Council of the European Union (2021*). Council Resolution on a strategic framework for European cooperation in education and training towards the European Education Area and beyond (2021-2030).* Official Journal of the European Union, 2021/C 66/01.

Daugherty, M. K., Carter, V., and Swagerty, L. (2014). *Elementary STEM education: The future for technology and engineering education? Journal of STEM teacher education*, *49*(1): 7.

Draghi, M. (2024). *The future of European competitiveness*. European Commission, September 2024. https://commission.europa.eu/topics/strengthening-european-competitiveness/eu-competitiveness-looking-ahead_en.

Department of Homeland Security (2023). *Update to the Department of Homeland Security STEM designated degree program list.* Federal Register, 88, 44381-44383. Docket No. ICEB-2022-0016. RIN 1653-ZA36. Document Number 2023-14807.

Driver, R., Asoko, H., Leach, J., Scott, P. and Mortimer, E. (1994). *Constructing scientific knowledge in the classroom*, Educational researcher, 23(7): 5-12, https://doi.org/10.3102/0013189X023007005.

Eastwell, P. (2002). *Social constructivism.* The Science Education Review, 1(3): 82-86

Eloundou, T., Manning, S., Mishkin, P., and Rock, D. (2023). *Gpts are gpts: An early look at the labor market impact potential of large language models, arXiv preprint arXiv:2303.10130*.

European Commission, Directorate-General for Education, Youth, Sport and Culture (2021). Girls' career aspirations in STEM, Publications Office of the European Union, Luxembourg, https://data.europa.eu/doi/10.2766/52684.

European Commission, Directorate-General for Education, Youth, Sport and Culture (2024). *The twin challenge of equity and excellence in basic skills in the EU – An EU comparative analysis of the PISA 2022 results*, Publications Office of the European Union, Luxembourg, https://data.europa.eu/doi/10.2766/881521.

Eisner, B., Kattmann, U., Kremer, M., Langlet, J., Plappert, D. and Ralle, B. (2019). *Common Reference Framework for the Natural Sciences (CRFS).* Minimum Standards for Natural Science-Related Education. A Suggestion. Third revised version.

Feenberg, A. (2002). *Transforming technology: A critical theory revisited.* New York: Oxford University Press.

Florida Department of Education (2009). *Expanding Education from STEM to STEAM. Preparing Florida's Students to Thrive in the 21st Century*, http://campusclubmilledgeville.org/images/EducationforFloridaRoadmap.pdf.

Fraillon, J. and Rožman, M. (2024). *International Computer and Information Literacy Study, 2023 Assessment Framework*, The International Association for the Evaluation of Educational Achievement (IEA).

Fraillon, J., Ainley, J., Schulz, W., Friedman, T., and Gebhardt, E. (2014). *Preparing for life in a digital age: The IEA International Computer and Information Literacy Study international report,* Springer Nature.

Freeman, B., Marginson, S., and Tytler, R. (Eds.) (2014). *The age of STEM: Educational policy and practice across the world in science, technology, engineering and mathematics.* Routledge.

Freeman, B., Marginson, S., and Tytler, R. (2019). *An international view of STEM education.* STEM Education 2.0: 350–363, Brill.

Frey, C. B. and Osborne, M. A. (2017). *Technological revolutions and work in the age of automation.* Journal of Economic Perspectives, 31(2): 185-208.

Gonzalez, H. B., and Kuenzi, J. J. (2012). Science, Technology, engineering, and mathematics (STEM) education: A primer, Congressional Research Service, Library of Congress, Washington DC, https://fas.org/sgp/crs/misc/R42642.pdf.

Gresnigt, R., Taconis, R., van Keulen, H., Gravemeijer, K. and Baartman, L. (2014). *Promoting science and technology in primary education: a review of integrated curricula,* Studies in Science Education, 50(1): 47-84, https://doi.org/10.1080/03057267.2013.877694.

Herro, D., Quigley, C., and Cian, H. (2018). *The Challenges of STEAM Instruction: Lessons from the Field,* Action in Teacher Education, 41: 172-190, https://doi.org/10.1080/01626620.2018.1551159.

Holbrook, J., Rannikmäe, M., and Soobard, R. (2020). *STEAM Education—A transdisciplinary teaching and learning approach.* In: Science Education in Theory and Practice (465-477). Springer, Cham.

Honey M., Pearson, G., Schweingruber, H. (2014). *STEM Integration in K-12 Education: Status, Prospects, and an Agenda for Research*. Natl. Acad. Press, Washington, DC.

Horváth, A., Baïdak, N., Motiejunaite-Schulmeister, A., and Noorani, S. (2022). *Increasing Achievement and Motivation in Mathematics and Science Learning in Schools, Eurydice Report*. European Education and Culture Executive Agency, European Commission.

Johnson, C. C., Kahle, J. B., and Fargo, J. D. (2007). *Effective teaching results in increased science achievement for all students,* Science Education, 91(3): 371-383.

Kelley, T. and Knowles, J. (2016). *A conceptual framework for integrated STEM education.* International Journal of STEM Education, 3: 1-11, https://doi.org/10.1186/S40594-016-0046-Z.

Kennedy, T. J. and Sundberg, C. W. (2020). *21st-century skills.* In: Science Education in Theory and Practice (479-496). Springer, Cham.

Kennedy, T. and Odell, M. (2014). *Engaging Students in STEM Education*, Science education international, 25: 246-258.

Letta, E. (2024). *Much more than a market – Speed, Security, Solidarity: Empowering the Single Market to deliver a sustainable future and prosperity for all EU Citizens.* European Commission, April 2024. *https://www.consilium.europa.eu/media/ny3j24sm/much-more-than-a-market-report-by-enrico-letta.pdf.*

Li, Y., Wang, K., Xiao, Y., and Froyd, J. E. (2020). *Research and trends in STEM education: A systematic review of journal publications*, International journal of STEM education, 7(1): 1-16.

Maass, K., Geiger, V., Ariza, M. R., and Goos, M. (2019). *The role of mathematics in interdisciplinary STEM education,* ZDM Mathematics Education, 51: 869-884.

Martín-Páez, T., Toscano, M. O., and Manzano, S. (2019). *What are we talking about when we talk about STEM education? A review of the literature,* Science Education, 103(4): 799-822.

Mejias, S., Thompson, N., Sedas, R. M., Rosin, M., Soep, E., Peppler, K., Roche, J., Wong, J., Hurley, M., Bell, P. and Bevan, B. (2021). *The trouble with STEAM and why we use it anyway,* Science Education, 105(2): 209-231.

Miao, Z. and Reynolds, D. (2017). *The effectiveness of mathematics teaching in primary schools: Lessons from England and China,* Routledge.

Mullis, I. V. S. and Martin, M. O. (2017). *TIMSS 2019 Assessment Frameworks*, Boston College, TIMSS & PIRLS International Study Center, http://timssandpirls.bc.edu/timss2019/frameworks.

Mullis, I. V. S., Martin, M. O., Foy, P., Kelly, D. L., and Fishbein, B. (2020). *TIMSS 2019 International Results in Mathematics and Science,* Boston College, TIMSS & PIRLS International Study Center, https://timssandpirls.bc.edu/timss2019/international-results/.

Mullis, I. V. S., Martin, M. O., and von Davier, M. (Eds.) (2021). *TIMSS 2023 Assessment Frameworks.* Boston College, TIMSS & PIRLS International Study Center, https://timssandpirls.bc.edu/timss2023.

Mullis, I. V. S., Martin, M. O., Fishbein, B., Foy, P., and Moncaleano, S. (2021). *Findings from the TIMSS 2019 problem solving and inquiry tasks,* Boston College, TIMSS & PIRLS International Study Center, https://timssandpirls.bc.edu/timss2019/psi/.

National Academy of Engineering and National Research Council (2009). *Engineering in K-12 Education. Understanding the Status and Improving the Prospects.* Washington, D.D.: The National Academies Press.

National Council of Teachers of Mathematics (2014). *Principles to actions: Ensuring mathematical success for all*, Reston, VA.

National Research Council (2011). *Successful K-12 STEM Education: Identifying Effective Approaches in Science, Technology, Engineering, and Mathematics.* The National Academies Press.

OECD (2015). *The ABC of Gender Equality in Education: Aptitude, Behaviour, Confidence*, OECD Publishing, Paris, http://dx.doi.org/10.1787/9789264229945-en.

OECD (2017). *PISA 2015 collaborative problem solving framework.* PISA 2015 Assessment and Analytical Framework: Science, Reading, Mathematic, Financial Literacy and Collaborative Problem Solving, 131-188.

OECD (2018). *Preparing our youth for an inclusive and sustainable world: the OECD PISA global competence framework*, OECD Publishing, Paris, http://www.oecd.org/pisa/HandbookPISA-2018-Global-Competence.pdf.

OECD (2019). *PISA 2021 creative thinking framework* (third draft), PISA, OECD Publishing, Paris.

OECD (2023). *PISA 2022 Assessment and Analytical Framework*, PISA, OECD Publishing, Paris, https://doi.org/10.1787/dfe0bf9c-en.

Osborne, J. and Pimentel, D. R. (2023). *Science education in an age of misinformation*, Science Education, 107:553-571.

Perignat, E. and Katz-Buonincontro, J. (2019). *STEAM in practice and research: An integrative literature review, Thinking Skills and Creativity, 31*: 31-43.

PIAAC Literacy Expert Group (2009a). *PIAAC Literacy: A Conceptual Framework*, OECD Education Working Papers, No. 34, OECD Publishing, Paris, https://doi.org/10.1787/220348414075.

PIAAC Numeracy Expert Group (2009b). *PIAAC Numeracy: A Conceptual Framework*, OECD Education Working Papers, No. 35, OECD Publishing, Paris, https://doi.org/10.1787/220337421165.

PIAAC Literacy Expert Group (2009c). *PIAAC Problem Solving in Technology-Rich Environments: A Conceptual Framework*, OECD Education Working Papers, No. 36, OECD Publishing, Paris, doi:10.1787/220262483674.

Pokropek, A. and Borgonovi, F. (2020). *Linking via pseudo-equivalent group design: Methodological considerations and an application to the PISA and PIAAC assessments.* Journal of Educational Measurement, *57*(4): 527-546.

Pokropek, A., Marks, G. N., Borgonovi, F., Koc, P., & Greiff, S. (2022). *General or specific abilities? Evidence from 33 countries participating in the PISA assessments.* Intelligence, 92, 101653.

Prawat, R. S. and Floden, R. E. (1994). *Philosophical perspectives on constructivist views of learning,* Educational Psychologist, 29(1): 37-48, https://doi.org/10.1207/s15326985ep2901_4.

Rimes, C. and León de la Barra, B. (2014). Introduction to the history of STEM education. *Journal of STEM Education: Innovations and Research, 15*(1), 20-26.

Ritz, J. M. and Fan, S. C. (2015). *STEM and technology education: International state-of-the-art*, International Journal of Technology and Design Education, 25: 429-451.

Sanders, M. (2009). STEM, STEM Education, STEMmania. *The Technology Teacher*, *68*(4), 20–26.

Sjøberg, S., & Jenkins, E. (2022). *PISA: a political project and a research agenda.* Studies in Science Education, 58(1), 1-14.

Strimel, G. and Grubbs, M. E. (2016). *Positioning technology and engineering education as a key force in STEM education,* Journal of Technology Education, 27(2): 21-36.

The Council of the European Union (2018). *Council Recommendation on Key Competences for Lifelong Learning*, European Commission: Brussels, Belgium.

Wise, K. C. and Okey, J. R. (1983). *A meta-analysis of the effects of various science teaching strategies on achievement,* Journal of Research in Science Teaching, 20(5): 419-435.

Xie, Y., Fang, M., and Shauman, K. (2015). *STEM Education,* Annual review of sociology, 41: 331-357, https://doi.org/10.4135/9781506326139.n669.

Yakman, G. (2008). *STP@M: Understanding the whole by examining the parts,* Procedia - Social and Behavioral Sciences, 1(1): 1821-1830.

Yakman, G. and Lee, H. (2012). *Exploring the exemplary STEAM education in the US as a practical educational framework for Korea,* Journal of the Korean Association for Science Education, 32(6): 1072-1086.

Zamorano, L. et al. (2019). *Interdisciplinary integration of the STEM curriculum and the arts: A collaborative project*. Journal of STEM Education: Innovations and Research, 20(4): 5-10.

Zeidler, D.L. (2016). *STEM education: A deficit framework for the twenty first century? A sociocultural socioscientific response.* Cultural Studies of Science Education, 11: 11-26.

List of abbreviations and definitions

21CS	21st-century skills
CIL	Computer and Information Literacy
EU	European Union
ICILS	International Computer and Information Literacy Study
ICT	Information and Communication Technologies
IEA	International Association for the Evaluation of Educational Achievement
OECD	Organisation for Economic Co-operation and Development
PISA	Programme for International Student Assessment
PIAAC	Programme for the International Assessment of Adult Competencies
SMET	Science, Mathematics, Engineering, and Technology
STEAM	Science, Technology, Education, Arts, and Mathematics
STEM	Science, Technology, Education, and Mathematics
TIMSS	Trends in International Mathematics and Science Study

List of figures

Figure 1. Number of articles on STEM education by year 20

List of tables

Table 1. STEM Competencies Summary 16

Table 2. Competency Categories, National Research Council 17

Table 3. Summary of PISA core domains 31

Table 4. Summary of PISA assessment, including optional components for EU countries 36

Table 5. Summary of TIMSS core domains 37

Table 6. Summary of TIMSS assessment for EU countries 40

Table 7. Summary of PIAAC domains 42

Table 8. Summary of PIAAC assessment for EU countries 43

Table 9. Summary of ICLS 2023 domains 44

Table 10. Summary of ICILS assessment for EU countries 45

Getting in touch with the EU

In person

All over the European Union there are hundreds of Europe Direct centres. You can find the address of the centre nearest you online (european-union.europa.eu/contact-eu/meet-us_en).

On the phone or in writing

Europe Direct is a service that answers your questions about the European Union. You can contact this service:

— by freephone: 00 800 6 7 8 9 10 11 (certain operators may charge for these calls),
— at the following standard number: +32 22999696,
— via the following form: european-union.europa.eu/contact-eu/write-us_en.

Finding information about the EU

Online

Information about the European Union in all the official languages of the EU is available on the Europa website (european-union.europa.eu).

EU publications

You can view or order EU publications at op.europa.eu/en/publications. Multiple copies of free publications can be obtained by contacting Europe Direct or your local documentation centre (european-union.europa.eu/contact-eu/meet-us_en).

EU law and related documents

For access to legal information from the EU, including all EU law since 1951 in all the official language versions, go to EUR-Lex (eur-lex.europa.eu).

EU open data

The portal data.europa.eu provides access to open datasets from the EU institutions, bodies and agencies. These can be downloaded and reused for free, for both commercial and non-commercial purposes. The portal also provides access to a wealth of datasets from European countries.

Science for policy

The Joint Research Centre (JRC) provides independent, evidence-based knowledge and science, supporting EU policies to positively impact society

EU Science Hub
Joint-research-centre.ec.europa.eu

Publications Office
of the European Union