ATS STEM

Report #1 of
ATS STEM Report Series

STEM Education in Schools: What Can We Learn from the Research?

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This is Report #1 of #5 in the ATS STEM Report Series. The other reports in the series are as follows and are available from the project website: **http://www.atsstem.eu/ireland/reports/**

- Report #1: STEM Education in Schools: What Can We Learn from the Research?
- Report #2: Government Responses to the Challenge of STEM Education: Case Studies from Europe
- Report #3: Digital Formative Assessment of Transversal Skills in STEM: A Review of Underlying Principles and Best Practice
- Report #4: Virtual Learning Environments and Digital Tools for Implementing Formative Assessment of Transversal Skills in STEM
- Report #5: Towards the ATS STEM Conceptual Framework

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FOREWORD

Assessment of Transversal Skills in STEM (ATS STEM) is an innovative policy experimentation project being conducted across eight European Union countries through a partnership of 12 educational institutions **(www.atsstem.eu)**. The project is funded by Erasmus+ (Call reference: EACEA/28/2017 - European policy experimentations in the fields of Education and Training, and Youth led by high-level public authorities). The project aims to enhance formative digital assessment of students' transversal skills in STEM (Science, Technology, Engineering, and Mathematics). ATS STEM is co-financed by the ERASMUS+ Programme (Key Action 3 – Policy Experimentation). The project partnership comprises ministries of education, national and regional education agencies; researchers and pilot schools.

The countries and regions in which the digital assessment for STEM skill are being piloted are **Austria, Belgium/ Flanders, Cyprus, Finland, Ireland, Slovenia, Spain/Galicia,** and **Sweden** as per below:

- Dublin City University, Ireland
- H2 Learning, Ireland
- Kildare Education Centre, Ireland
- Danube University Krems, Austria
- Go! Het Gemeenschapsonderwijs, Belgium
- Cyprus Pedagogical Institute, Cyprus
- University of Tampere, Finland
- Ministry of Education, Science and Sport, Slovenia
- National Education Institute Slovenia
- University of Santiago De Compostela, Spain
- Consejería De Educación, Universidad Y Fp (Xunta De Galicia), Spain
- Haninge Kommun, Sweden

Dublin City University (DCU) is the project coordinator. A core element of DCU's vision is to be a globally-significant university that is renowned for its discovery and translation of knowledge to advance society. DCU has an interdepartmental team of experts from three different research centres bringing their combined expertise to bear to help lead and deliver the project goals. These centres have expertise in digital learning, STEM education and assessment and are respectively the National Institute for Digital Learning (NIDL), the Centre for the Advancement of STEM Teaching and Learning (CASTeL) and the Centre for Assessment Research, Policy and Practice in Education (CARPE).

NIDL
National Institute
for Digital Learning

The National Institute for Digital Learning (NIDL) aims to be a world leader at the forefront of designing, implementing and researching new blended, on-line and digital (BOLD) models of education **(https://www.dcu.ie/nidl/index.shtml)**. The NIDL'S mission is to design, implement and research distinctive and transformative models of BOLD education which help to transform lives and societies by providing strategic leadership, enabling and contributing to world-class scholarship, and promoting academic and operational excellence.

CASTeL
Centre for the Advancement of STEM Teaching and Learning

The Centre for the Advancement of STEM Teaching and Learning (CASTeL) is Ireland's largest research centre in STEM education **(http://castel.ie/)**. CASTeL's mission is to support the development of STEM learners from an early age, and so enhance the scientific, mathematical and technological capacity of society. CASTeL encompasses research expertise from across the Faculty of Science and Health and the DCU Institute of Education, one of Europe's largest educational faculties.

CARPE
Centre for Assessment Research,
Policy and Practice in Education

The Centre for Assessment Research, Policy and Practice in Education (CARPE) is supported by a grant from Prometric to Dublin City University **(https://www.dcu.ie/carpe/index.shtml)**. The centre was established to enhance the practice of assessment across all levels of the educational system, from early childhood to fourth level and beyond.

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

This report (Report #1) was written as part of a research project titled, *Assessment of Transversal Skills in STEM (ATS STEM).* The project is funded by Erasmus+ (Call reference: EACEA/28/2017 - European policy experimentations in the fields of Education and Training, and Youth led by high-level public authorities). The report is based on outputs related to the first deliverable in work package one of ATS STEM project, as outlined in Appendix A—namely *STEM Conceptual Framework* (WP1).

The findings of a systematic literature review and synthesis of journal publications over the period 2010-2019 are presented in this report. The selection of literature for final inclusion in this review was informed by the identification of five research questions as deemed most relevant to the focus of the ATS STEM project, namely:

1. What are the different definitions of STEM education?
2. What are the core STEM competences?
3. What does an integrated STEM education curriculum look like?
4. How do teachers understand the learning domain and its perceived goals as well as the most appropriate way to organise learning activities?
5. What is assessed in STEM education?

Overall, 79 publications were identified as relevant for inclusion in this review, and the findings of the emergent themes from our analysis of the selected literature in relation to each of the five research questions are presented in this report.

The examination of different definitions of STEM education, as reported, revealed 23 sub-characteristics of STEM education that have been classified as the seven characteristics of integrated STEM education: namely (1) Core STEM Competences; (2) Problem-Solving Design and Approaches; (3) Disciplinary and Interdisciplinary Knowledge; (4) Engineering Design and Practices; (5) Appropriate Use and Application of Technology; (6) Use of Real-World Contexts; and (7) Appropriate Pedagogical Practices. Review of this body of literature identified 243 specific STEM skills and competences, which were classified as eight Core STEM Competences: namely (1) collaboration, (2) problem-solving, (3) innovation and creativity, (4) critical thinking, (5) disciplinary skills and competences, (6) self-regulation, (7) communication and (8) metacognitive skills.

Designing integrated experiences and providing intentional and explicit support for students is necessary in order to build knowledge and competences both within the disciplines and across disciplines. Connecting ideas across disciplines is challenging when students have little or no understanding of the relevant ideas in the individual disciplines. The use of appropriate resources (including use of digital tools and resources), innovative pedagogies and curriculum innovation, are particularly important in facilitating an integrated approach to STEM teaching and learning in schools. Several studies highlight the need for teachers to engage in professional learning and collaboration with teachers from other disciplines to identify cross-cutting themes. This collaboration is essential to support teachers in order to deepen their knowledge about other disciplines, and become familiar with current practices of integrated STEM curricula. There were limited examples of tools and strategies that have been used by teachers in the STEM classroom reported in the literature with many studies emphasising the need to support teachers' developing appropriate pedagogical knowledge and assessment practices for integrated STEM education.

INTRODUCTION

STEM is a central concern of educational policymakers across the world as it is considered essential for global economic prosperity (e.g. Martin-Paez et. al., 2019; Thomas & Watters, 2015). Several different reasons are often provided to justify initiatives to promote STEM education, some of which are social, environmental and/or economic development (Kelley & Knowles, 2016), catching up with economic competition (Corlu et al., 2014), innovation (Corlu et al., 2014; Sanders, 2009), the low number of STEM graduates (European Schoolnet, 2018), and attracting STEM students for the job market (European Schoolnet, 2018; Nistor et al., 2018). Marginson et al. (2013) observe that countries with strong and dynamic economies tend to be those with successful education systems that place a high value on STEM education. There is a global recognition within the labour market of the imminent shortages of STEM workers at all levels, both those working in professional and in other roles. For example, Europe faces a shortage of around 756,000 ICT professionals by 2020, with a lack of synergy between educational systems and the requirements of the labour market (Palotai, 2017). Most countries are now aware of these imminent shortages and are taking pro-active action to address this situation.

In Europe, going beyond just the economic imperative, European Schoolnet (2018, p.14) presents the aims of promoting STEM initiatives as to:

- popularise sciences (increase STEM literacy),
- increase STEM uptake by promoting STEM careers,
- engage the gifted and talented with challenging STEM initiatives,
- reduce the gender gap in STEM.

Even though one of the aims is to increase STEM literacy, a number of reports point out current failures of educational systems in helping students to understand how to solve real-world problems using knowledge gained through STEM disciplines (Bybee, 2013; National Governors Association, 2007; Ritz & Fan, 2015).

Moreover, many issues remain unsolved—for example, STEM education is a contested term which does not have a unified definition (Bybee, 2013); and implementation of a coherent approach to STEM education continues to be vague (Granshaw, 2016). Definitions of STEM range from simple descriptions of the four STEM disciplines (Science, Technology, Engineering and Mathematics), to educational approaches at the intersections of any number of the four disciplines, to a more complex understanding of all four STEM disciplines in an integrated manner (Bybee, 2013; Sanders, 2009). Bybee (2013) presents the different perspectives of STEM education viewing STEM as (a) science or maths, (b) both science and maths, (c) science by incorporating technology, engineering or maths, (d) a quartet of separate disciplines, (e) science and maths are connected by a technology or engineering program, (f) coordination across disciplines, (g) combining two or three disciplines, (h) complementary overlapping across disciplines, and (i) transdisciplinarity course or program.

Aligned with these different interpretations of STEM, the way of bringing STEM disciplines together also varies, such as integrated STEM and interdisciplinary approaches (Martin-Paez et al., 2019). Researchers in the area assert that STEM education must 'remove the traditional barriers' between science, technology, engineering and mathematics (Kennedy & Odell, 2014, p.254). This perspective reflects the 'real world' where individuals must draw on a wide range of integrated skills from overlapping knowledge bases to solve problems. Stohlmann et al. (2012) note that there are many benefits to integrated education with Furner and Kumar (2007, p. 168) commenting that an 'integrated curriculum provides opportunities for more relevant, less fragmented, and more stimulating experiences for learners. While this integrated approach has many benefits, it is difficult to implement as the traditional segmented or 'silo' approach to the delivery of curriculum subjects has dominated educational systems in many countries (Granshaw, 2016).

It follows as a basic tenant of this report that the creation of an integrated curriculum is necessary for high-quality STEM education and such an approach involves significant reform. Smith et al. (2007) recommend that to deliver such reforms requires a coherent conceptual framework that outlines the relationship between and the practical integration of each of the four disciplines. Accordingly, this type of framework and related curriculum reform should be a priority for all policymakers within STEM education. Such a framework will have major implications for how teachers understand the learning domain of STEM education and its perceived goals as well as the most appropriate way to organise learning activities. It should also consider the role of assessment and develop guidelines for effective formative and summative assessments which will help teachers better understand the goals of STEM education. There is some early-stage work underway in this area in the United States (the US) but developments are relatively immature at a European level (Kelley & Knowles, 2016).

Educational systems typically 'take their cues regarding their goals for instruction and learning from the types of tasks found in state, national and international assessments' (Gane et al., 2018). For example, it is not surprising that the creation of classroom-based digital tasks and activities that can cultivate '21st Century Skills' in students is becoming a priority for all education systems, since PISA (OECD, 2017) began to develop technology-based assessments that measure these competences. It has been broadly recognised that STEM education allows students to develop a range of transversal skills (STEM Education Review Group, 2016); therefore, it is particularly important for STEM educators to develop such tasks. In keeping with best practice recommendations for teaching maths and science (Daniels et al., 2005), these tasks should use contemporary models of assessment and meaningfully integrate technology as part of instruction as a matter of priority.

The widespread proliferation of technology provides a wide range of resources that can be used to support teaching, learning, and assessment in STEM. Indeed, STEM assessments have already begun to utilise technology to achieve this, as discussed in Reports #3 and #4 of this series. For example, Quellmalz et al. (2013) developed a simulation-based assessment for 12-year-old students to develop their knowledge of ecosystems using the SimScientists platform. The simulation was designed to measure students' progress as it related to three key science constructs – declarative knowledge (knowing 'what'), schematic knowledge (knowing 'why'), and procedural/ strategic knowledge (knowing 'how to use and apply').

Purpose and Aims of this Report

This report is as part of an Erasmus+ project entitled Assessment of Transversal Skills in STEM (ATS STEM), an innovative policy experimentation project being conducted across eight European Union countries through a partnership of 12 educational institutions. STEM education is a priority for all of the ATS STEM partners and each country/region is already engaged in implementing specific policy actions to promote the development of STEM knowledge and competences across their school sectors. The ATS STEM project aims to develop transversal STEM competences for students and appropriate digital assessment methods. The project will support teachers by customising their learning designs to better meet the needs of their students. This will be achieved through the creation of practical examples of how new Digitial Technologies can be harnessed to foster STEM skills and competences in students.

The long-term aim of the project will be linking policymakers to best practice examples, allowing for such practices to spread and be adopted towards affecting meaningful change and curriculum reform in STEM education. In a growing digital world, the creation of high-quality STEM learning and assessment tasks is more achievable than ever. Yet, recent research by O'Leary et al. (2018) acknowledges that very few examples of digital technology being used to develop authentic and practical learning and assessment tasks exist. This observation is particularly true in relation to STEM education. Hence, there is a need to develop a range of digital formative assessments to support STEM education and to explore what this looks like in the practical reality of teaching and learning settings.

In summary, the purpose of this first report is to provide a strong theoretical and research foundation regarding STEM Education, with particular respect to schools. The report aims to present examples of how STEM education has been defined and implemented in school curricula and how digital assessment of transversal skills and competences has been carried out.

Structure of this Report

The first section established the context for this report, Section Two presents the search methodology used to identify and select relevant publications and ensure the trustworthiness of this review. The selection of literature for final inclusion in this review was informed by the identification of five research questions[1] as deemed most relevant to the focus of the ATS STEM project, namely:

1. What are the different definitions of STEM education?
2. What are the core STEM competences?
3. What does an integrated STEM education curriculum look like?
4. How do teachers understand the learning domain and its perceived goals as well as the most appropriate way to organise learning activities?
5. What is assessed in STEM education?

Section Three provides a synthesis of literature on STEM Education reported from 2010 to the middle of 2019. Several definitions of STEM education are reported and this lack of consensus in defining STEM education causes plan student learning experiences (Radloff & Guzey, 2016). As previously mentioned, this report embraces the integration of all STEM subjects together in coherent activities to offer more authentic and meaningful STEM education. There are many reasons for adopting such an integrated approach - for example, STEM education often fails to translate innovations in policy into innovations in pedagogy and STEM disciplines (Murphy et al., 2017; Rudolph, 2008; Zeidler, 2016). For these reasons, this report asserts that STEM education must 'remove the traditional barriers' between science, technology, engineering, and mathematics. When the barriers between the STEM disciplines are removed, the literature suggests that an "integrated curriculum provides opportunities for more relevant, less fragmented and more stimulating experiences for learners" (Furner & Kumar, 2007, p.168).

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[1] These research questions were identified by Report#1 authors.

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SEARCH METHODOLOGY

A qualitative and intentional review (Randolph, 2009) was conducted of journal articles published during the period 2010-2019 using the Scopus database. The stages of the review process, adapted from those proposed by Bennett, Lubben, Hogarth, and Campbell (2005) for systematic reviews of research in science education, are described in Table 1.

Table 1: Stages of the review process (adapted from Martin-Paez et al., 2019)

Stage	Actions
Clarification and approach	Create a theoretical framework. Formulate research questions. Establish search key and inclusion criteria. Design review protocol and define categories considered for analysis
Search, review, and select	Scopus database search and review publications. Assess appropriateness for inclusion.
Analyse and interpret	Analyse research characteristics. In-depth understanding of included works. Interpret and discuss the results obtained. Agree publications to be included in the review.
Draft report	Structure information. Present results and discuss Submit implications and conclusions.

The Scopus database was utilised as it is reported to be the largest abstract and citation database of peer-reviewed literature including scientific journals, books, and conference publications (Why choose Scopus?, 2019). Launched in late November 2004, Scopus, owned by Elsevier, claims to be the largest abstract and citation database containing both peer-reviewed research literature and as well as web sources. Scopus is a subscription-based service and claims to provide the most comprehensive overview of the world's research outputs in the fields of Science, Technology, Medicine, Social Sciences, and Arts and Humanities. This makes Scopus the most comprehensive repository for studies within the STEM discipline. Scopus matches author names to a high degree of accuracy because authors are always matched to their affiliations. Another advantage is that Scopus covers titles from all geographical regions. Non-English titles are included provided English abstracts appear with the publications (Agarwal et al., 2016). In addition, it has been reported that journal coverage in Scopus is more comprehensive than the Web of Science (WoS) database (Moya-Anegón et al., 2007). A recent comparison of the two databases concluded that WOS has strong coverage which goes back to 1990 and most of its journals written in English but Scopus covers a superior number of journals in the range from 1996 onwards (Chadegani et al., 2013). Given the focus of this current synthesis and review of literature relating to STEM education, and the focus on publications only from 2010 onwards, it was decided that Scopus would produce the most optimal results for this study.

The acronym STEM was introduced in 2001 by scientific administrators at the United States (US) National Science Foundation (NSF) to represent the collection of the disciplines of Science, Technology, Engineering, and Mathematics. Using the search term with the keyword "STEM Education" retrieved 2,637 publications in the Scopus database in the period from 2002 to 2019 (search conducted in August 2019) as shown in Figure 1.

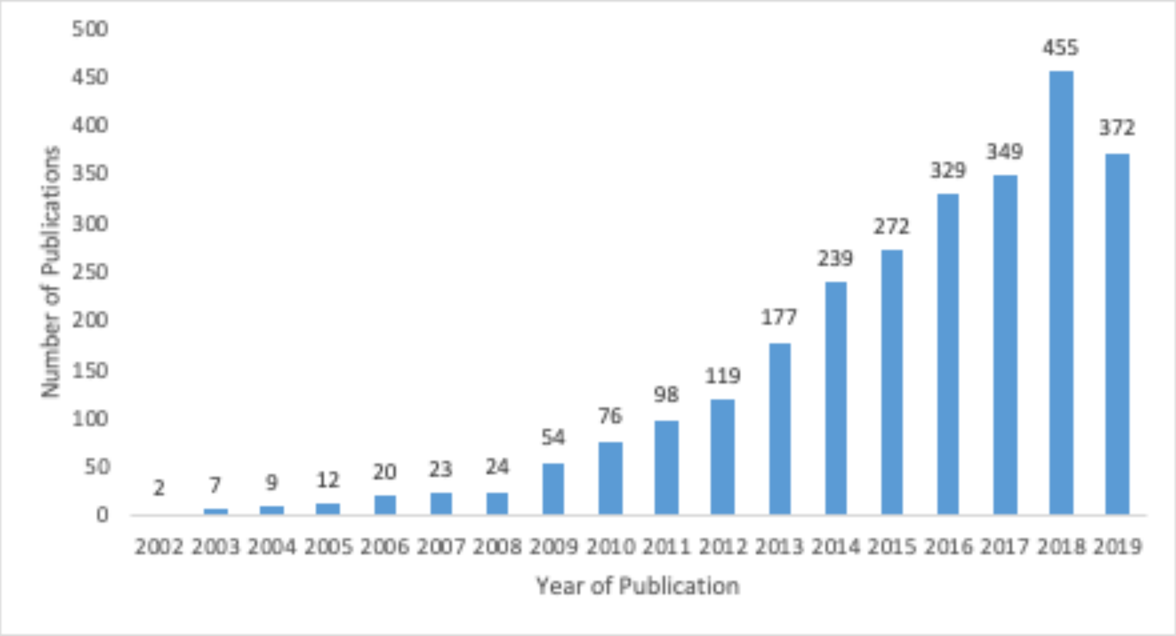

Figure 1: Number of publications retrieved by Scopus with search words "STEM Education" in the period from 2002-2019 (Accessed August 2019)

Since 2002, the concept of a STEM-focused curriculum has been extended to many countries beyond the US. However, the body of literature published on "STEM Education", between 2002 and 2019, is dominated by publications by authors from the US (59%, 1580 publications) as illustrated in Figure 2.

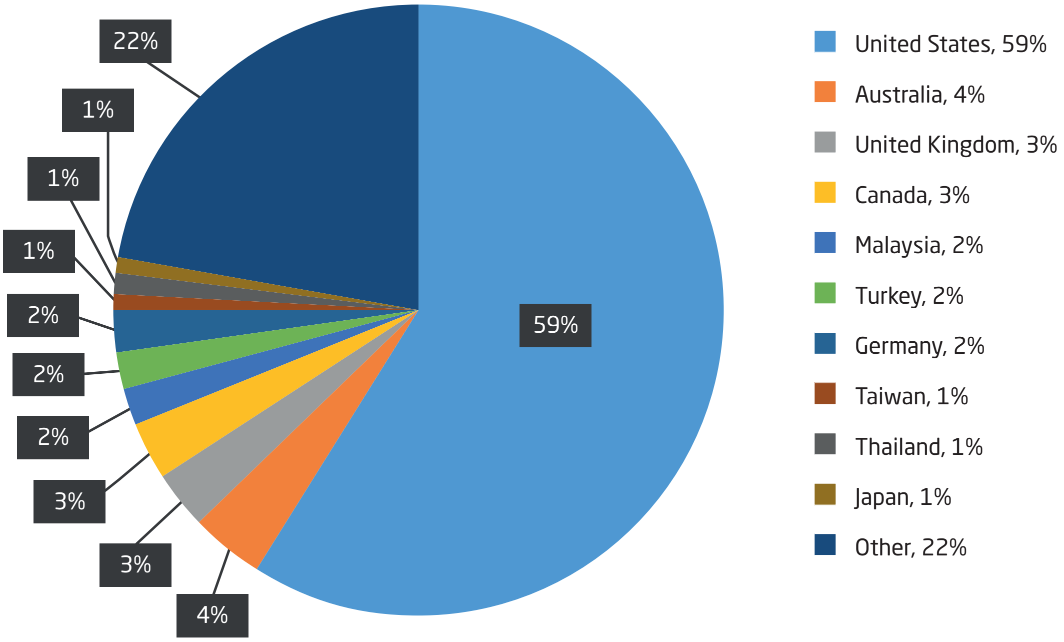

Figure 2: Publications retrieved with search term "STEM Education" (2002-2019) based on authors' country of affiliation

The decision to narrow down the current review to report on publications from 2010 onwards, was taken based on the substantialincrease in the use of the term "STEM Education" in published literature beyond that time period. As shown in Figure 1, from 2002 to 2010, there were 151 publications, compared to 2486 in the period from 2010 to 2019. However, since 2010 the number of publications related to the search term "STEM Education" has increased significantly over a ten-year period, e.g. from 54 in 2009 to 455 in 2018.

However, USA has maintained its dominance by publishing 57% (1417 publications) of the total number of publications in this period, as illustrated in Figure 3.

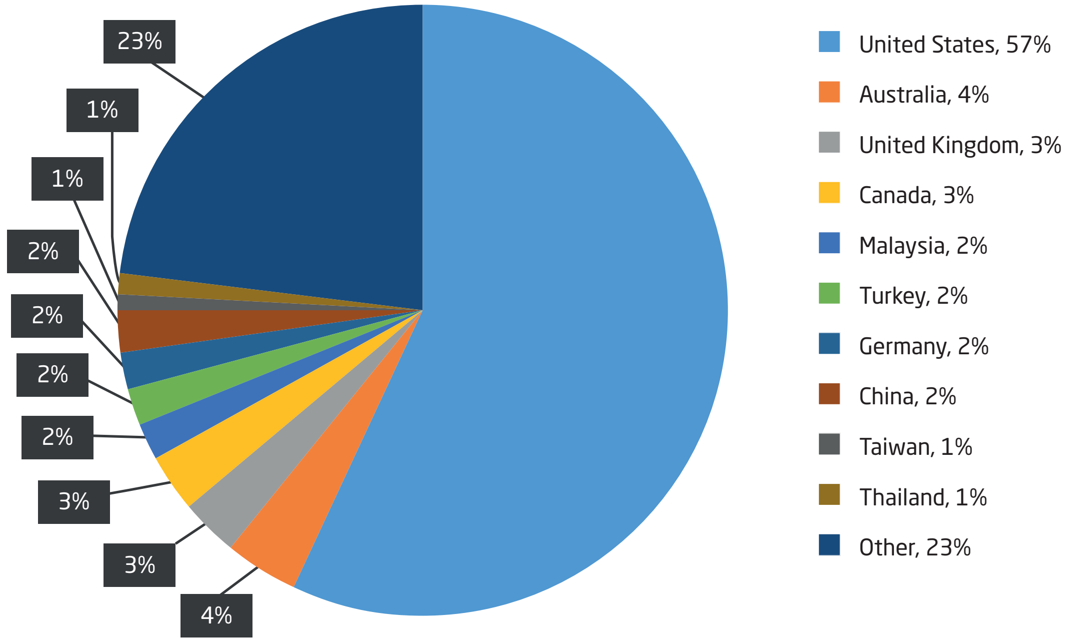

Figure 3: Publications retrieved with search term "STEM Education" (2010-2019) based on authors' country of affiliation

At the beginning of the reviewing process, the research team agreed on the keywords that were to be used to search the literature, established the inclusion/exclusion criteria, and designed the review protocol. The selection of publications for final inclusion in this review was informed by five research questions previously outlined in the introductory section.

1. What are the different definitions of STEM education?
2. What are the core STEM competences?
3. What does an integrated STEM education curriculum look like?
4. How do teachers understand the learning domain and its perceived goals as well as the most appropriate way to organise learning activities?
5. What is assessed in STEM education?

Search Criteria Used in This Review

The keywords used in this review were identified as “STEM education”, “STEM literacy”, “STEM learning”, “STEM teaching”, “STEM competenc*”[2] and “Schools”. The search was linked by the Boolean OR operator, refined via the Boolean AND operator, conducted in the Education and Educational Research category. To identify as many publications as possible, the searches were conducted using the title, abstract, and keyword or descriptor fields in the Scopus database.

Stringent inclusion and exclusion criteria were established in this review process and these criteria were used to determine whether a publication was qualified to be included in the list of selected publications. A publication was included in the review if it met the following criteria:

1. studies that are of the journal type only.
2. publications that specify keywords.
3. studies that state a STEM education intervention developed in any educational context in which preschool, elementary school, middle school, and high school participate.
4. studies that are adopting integrated STEM education.

Figure 4 below illustrates the stages of the review process and the result of applying these review criteria. The first keyword search “STEM Education” in the Scopus database generated a volume of 2637 publications, limited to publications in the English-language, in the date range 2002 to 2019. Figure 4 provides details on the number of publications excluded and remaining at each stage of the review process after applying the review criteria. When the search term was limited to use the search terms “STEM education”, “STEM literacy”, “STEM learning”, “STEM teaching”, and “STEM competenc*” the number of studies decreased to 1887 for the data range 2002 to 2019. As soon as the data range was further restricted to the range 2010 to 2019, the number of studies decreased from 1887 to 1798 and further 49 publications were removed that were still in press in August 2019.

Publication titles and abstracts were then screened based on several factors, as listed in Table 2, and a further 1437 publications were excluded. These factors included grey literature, poorly written abstracts, and if it was not clear that the publication addressed all of the four STEM disciplines. Table 2 provides an overview of the number of publications excluded and remaining at each stage of the review process, based on title and abstract resulting in 312 publications being identified for further review. Reference details of these 312 publications are included in Appendix B.

Table 2: Overview of the number of publications excluded/remaining at each stage of the review process

Exclusion Criteria	Number Excluded	Remaining Studies
Number of publications identified using the search terms “STEM education”, “STEM literacy”, “STEM learning”, “STEM teaching”, and “STEM competenc*”	1887 (initial number)	
Exclude 1999 to 2009	1209	1798
Exclude publications in press	49	1749
Exclude grey literature (conference proceedings etc.)	1061	688
Exclude poorly written abstracts	229	459
Exclude publications that do not address all four STEM disciplines	147	312

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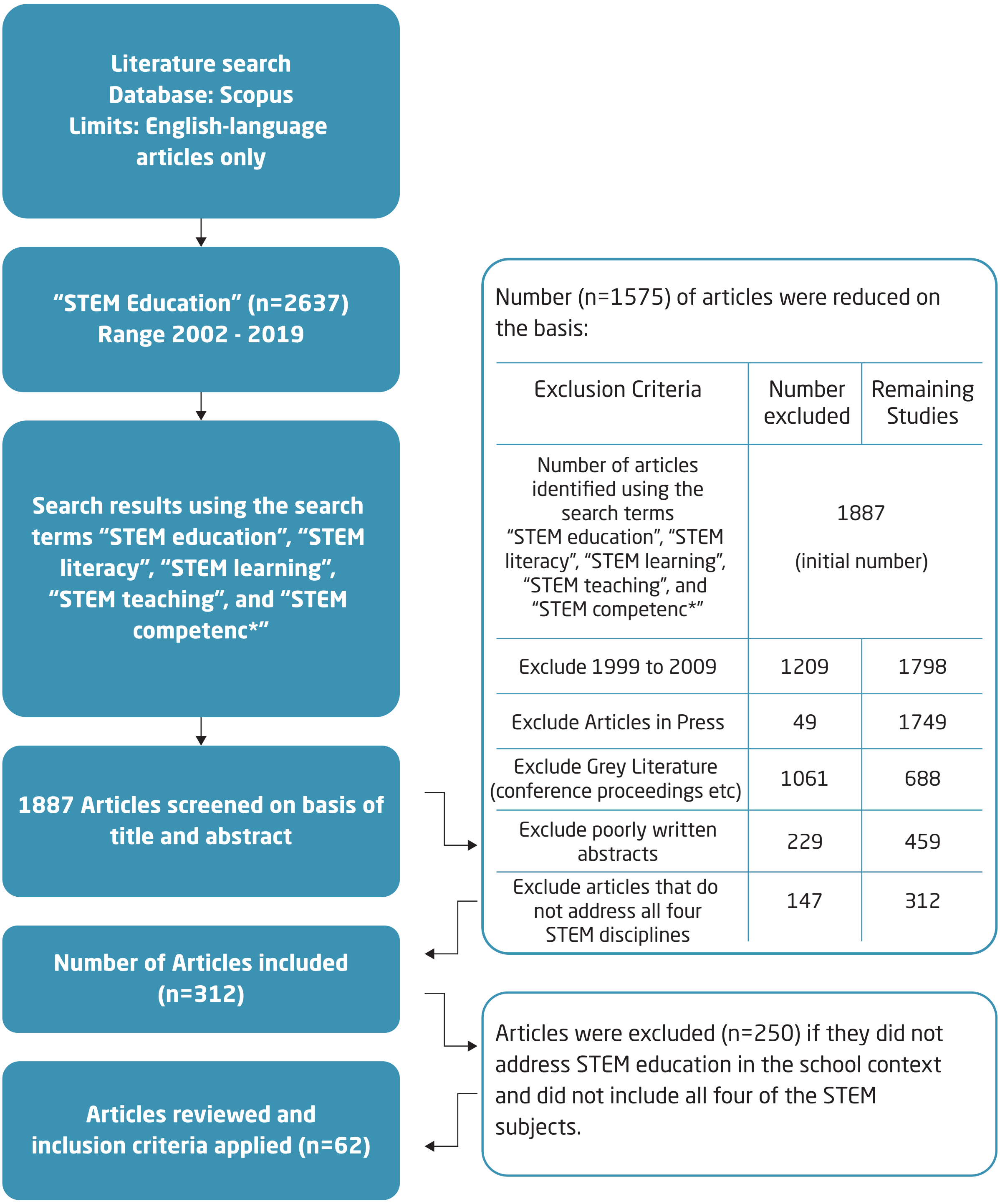
[2] Competenc* is used to capture related terms such as competence, competences, competency, competencies.



Number (n=1575) of articles were reduced on the basis:

Exclusion Criteria	Number excluded	Remaining Studies
Number of articles identified using the search terms "STEM education", "STEM literacy", "STEM learning", "STEM teaching", and "STEM competenc*"	1887 (initial number)	
Exclude 1999 to 2009	1209	1798
Exclude Articles in Press	49	1749
Exclude Grey Literature (conference proceedings etc)	1061	688
Exclude poorly written abstracts	229	459
Exclude articles that do not address all four STEM disciplines	147	312

Articles were excluded (n=250) if they did not address STEM education in the school context and did not include all four of the STEM subjects.

Figure 4: Overview of the stages of the review process and use of exclusion criteria

Final Selection of Publications

As mentioned above, the application of the review criteria resulted in 312 publications on the basis of the titles and abstracts of these publications. These 312 publications were further reviewed by reading the entire paper to ensure that they addressed "STEM education" in school context and involved all four STEM disciplines, rather than targeting only one or two of them. Reading the full publication resulted in the identification of 62 publications to be included in the final sample.

In order to conduct a careful review of these 62 publications, a coding procedure was constructed to capture the methodological and substantive features of each publication. The design of this coding procedure was completed by two researchers working together, while the use of this procedure was carried out independently by each researcher. The coding of the sample was based on reviewing the information provided in the full text of each publication and reviewing the content according to the following domains (See Table 3):

(a) characteristics of the study;
(b) conceptual framework of the study;
(c) identification of all four STEM disciplines;
(d) discussion and conclusions of the study.

Table 3: Analysed aspects and the procedure used for selecting publications (adapted from Martin-Paez et al., 2019)

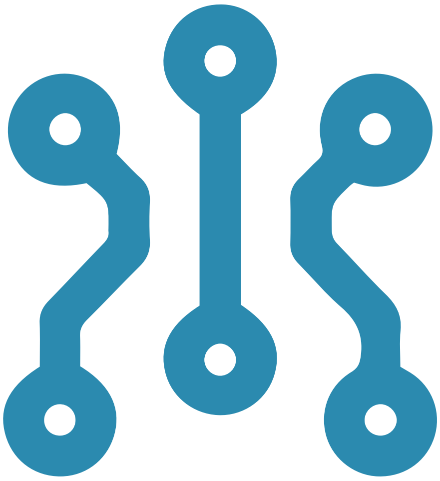
Characteristics of the study	The year of publication, design of the study, and educational stage in which the intervention was implemented are identified.
Conceptual framework	The conceptual foundation of each paper is analysed to identify the existence of definitions of STEM concepts if, on the contrary, these terms are not defined or are only named without arguing their conceptualization, these are not considered.
Identification of all 4 STEM disciplines	All 4 STEM disciplines (science, technology, engineering, and mathematics) have been explicitly discussed within the publication. For example, if a publication includes the acronym STEM and does not discuss all 4 disciplines and rather focuses on one or two of the disciplines, these publications are not considered for inclusion.
Discussion and conclusions of the study	The discussion and conclusions of each work is analysed, to identify and extract the benefits and key aspects for STEM education. In addition, the implications for future research and progress within in STEM is reviewed.

To enhance the validity of the methodology, a second member of the research team read the full text of each of the selected 62 publications. At the end of this process, 87% agreement was obtained for the analysis of the 62 publications in the sample. Both researchers then re-read the full texts of the eight publications that there were variances on. After this second review, a meeting was organised to review the variations in the evaluation of these eight publications. Which resulted in unanimous agreement with the decision to exclude a further eight publications primarily due to poorly written abstracts and/or the titles not as comprehensive as the study itself (See Table 4).

Table 4: Overview of the 8 publications removed from the selected list after double review

Author(s)	Year	Title of Publication	RQ
Cooper, S.	2010	Education K-12 Computational Learning	4,5
Crismond, D.P. & Adams, R.S.	2012	The Informed Design Teaching and Learning Matrix	3
Goethe, E.V. & Colina, C.M.	2018	Taking Advantage of Diversity within the Classroom	3
Hopfenbeck, T.N.	2019	Digital Education: Learning, Teaching and Assessment	4, 5
Johnson K.M.S.	2019	Implementing inclusive practices in an active learning STEM classroom	3
O'Leary, M. Scully, D., Karakolidis, A. & Pitsia V.	2018	The state-of-the-art in digital technology-based assessment	5
Pleasants J., Clough M.P., Olson J.K. & Miller G.	2019	Fundamental Issues Regarding the Nature of Technology: Implications for STEM Education	2,4
Wilson, S. B., & Varma-Nelson, P.	2016	Small groups, significant impact: A review of peer-led team learning research with implications for STEM education researchers and faculty	1

Consequently, there was agreement on the selection of 54 publications for inclusion in this study. The results from the coding of the final 54 selected studies are presented in Table 5 along with an outline for each article: (a) the first author; (b) year of publication; (c) title of the publication and (d) the alignment of the publication to one or more of the five research questions (RQ) developed for this review.



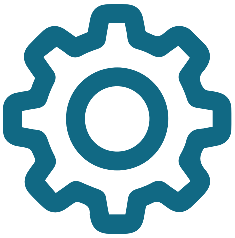


Table 5: Overview of the 54 selected publications selected for this review

Author(s)	Year	Title of Publication	RQ
Akcaoglu M., Rosenberg J.M., Ranellucci J. & Schwarz C.V.	2018	Outcomes from a self-generated utility value intervention on fifth and sixth-grade students' value and interest in science	5
Atkinson R.D.	2012	Why the current education reform strategy won't work	3,4
Bell D.	2016	The reality of STEM education, design and technology teachers' perceptions: a phenomenographic study	4,5
Blackley S. & Howell J.	2019	The next chapter in the STEM education narrative: Using robotics to support programming and coding	1,2,3
Bybee R.	2013	The case of STEM education: challenges and opportunities	1,2,3,4
Corlu M.S.	2013	Insights into STEM Education Praxis: An Assessment Scheme for Course Syllabi	1,4,5
Corlu M.S., Capraro Prof. R.M. & Capraro M.M.	2014	Introducing STEM education: Implications for educating our teachers for the age of innovation	1,4
EL-Deghaidy H.; Mansour N.; Alzaghibi M. & Alhammad K.	2017	Context of STEM Integration in Schools: Views from In-service Science Teachers	2,4
English L.D.	2017	Advancing Elementary and Middle School STEM Education	3
Ercan S.; Bozkurt A.E.; Taştan B. & Dağ I.	2016	Integrating GIS into science classes to handle STEM education	4
European Schoolnet	2018	STEM Education Policies in Europe	3,4
Freeman S.; Eddy S.L.; McDonough M.; Smith M.K.; Okoroafor N.; Jordt H. & Wenderoth M.P.	2014	Active learning increases student performance in science, engineering, and mathematics	3
Fuesting M. A.; Diekman A. B.; Boucher K. L.; Murphy M. C.; Manson D. L. & Safer B. L.	2019	Growing STEM: Perceived faculty mindset as an indicator of communal affordances in STEM	4
Gardner M. & Tillotson J.W.	2019	Interpreting Integrated STEM: Sustaining Pedagogical Innovation Within a Public Middle School Context	3,4
Guzdial M. & Morrison B.	2016	Growing Computer Science Education into a STEM Education Discipline	5
Hallström, J. & Schönborn, K. J.	2019	Models and modelling for authentic STEM education: Reinforcing the argument	3
Hodges G.; Jeong S.; McKay P.; Robertson T. & Ducrest D.	2016	Opening Access to STEM Experiences One Day at a Time: Successful Implementation of a School-Wide iSTEM Day	1,2,3

Author(s)	Year	Title of Publication	RQ
Hudson P.; English L.D.; Dawes L.; King D. & Baker S.	2015	Exploring links between pedagogical knowledge practices and student outcomes in STEM education for primary schools	1,3,5
Ibáñez M.B. & Delgado-Kloos C.	2018	Augmented reality for STEM learning: A systematic review	3,5
Jagannathan R.; Camasso M.J. & Delacalle M.	2019	Promoting cognitive and soft skills acquisition in a disadvantaged public-school system: Evidence from the Nurture thru Nature randomized experiment	2,3,5
Jeong, H.; Hmelo-Silver, C. E. & Jo, K.	2019	Ten years of Computer-Supported Collaborative Learning: A meta-analysis of CSCL in STEM education during 2005-2014	3,4,5
Kalaian S.A.; Kasim R.M. & Nims J.K.	2018	Effectiveness of Small-Group Learning Pedagogies in Engineering and Technology Education: A Meta-Analysis	4,5
Kelley T. R. & Knowles J. G.	2016	A conceptual framework for integrated STEM education	1,4
Kennedy T.J. & Odell M.R.L.	2014	Engaging Students in STEM Education	3,4
Kim C.; Kim D.; Yuan J.; Hill R.B.; Doshi P. & Thai C.N.	2015	Robotics to promote elementary education pre-service teachers' STEM engagement, learning, and teaching	2,4
Kurup M.P.; Li X.; Powell G. & Brown M.	2019	Building future primary teachers' capacity in STEM: based on a platform of beliefs, understandings and intention	2,4
Lamb R.; Akmal T. & Petrie K.	2015	Development of a cognition-priming model describing learning in a STEM classroom	1,3
Lesseig K.; Slavit D. & Nelson T.H.	2017	Jumping on the STEM bandwagon: How middle grades students and teachers can benefit from STEM experiences	1,2,3,4
Margot K.C. & Kettler T.	2019	Teachers' perception of STEM integration and education: a systematic literature review	3,4
Martin-Paez T., Aguilera D., Perales-Palacios F.J. & Vílchez-González J.M.	2019	What are we talking about when we talk about STEM education? A review of literature	1,2
Mohd Shahali E.H.; Halim L.; Rasul M.S.; Osman K. & Arsad N.M.	2019	Students' interest towards STEM: a longitudinal study	3
Moore TJ, Johnson CC, Peters-Burton EE, Guzey SS	2016	STEM road map: A framework for integrated STEM education	1,3,4
Mustafa N.; Ismail Z.; Tasir Z. & Mohamad Said M.N.H.	2016	A meta-analysis on effective strategies for integrated STEM education	1,2,3

Author(s)	Year	Title of Publication	RQ
Nistor, A., Gras-Velazquez, A., Billon, N. & Mihai, G.	2018	STEM Education Practices in Europe	3,4
Park M.H.; Dimitrov D.M.; Patterson L.G. & Park D.Y.	2017	Early childhood teachers' beliefs about readiness for teaching science, technology, engineering, and mathematics	4
Radloff J. & Guzey S.	2016	Investigating Preservice STEM Teacher Conceptions of STEM Education	1,4
Ralls D.; Bianchi L. & Choudry S.	2018	'Across the Divide': Developing Professional Learning Ecosystems in STEM Education	3,4,5
Rasul M.S.; Zahriman N.; Halim L. & Rauf R.A.	2018	Impact of integrated STEM smart communities program on students scientific creativity	2,3
Ritz J.M. & Fan S.C.	2015	STEM and technology education: international state-of-the-art	3,4
Ryu M.; Mentzer N. & Knobloch N.	2019	Preservice teachers' experiences of STEM integration: challenges and implications for integrated STEM teacher preparation	1,4
Sánchez Carracedo, F.; Soler A.; Martín C.; López D.; Ageno A.; Cabré J.; Garcia J.; Aranda J. & Gibert K.	2018	Competency Maps: An Effective Model to Integrate Professional Competencies Across a STEM Curriculum	2,4
Sarican G. & Akgunduz D.	2018	The impact of integrated STEM education on academic achievement, reflective thinking skills towards problem solving and permanence in learning in science education	2,3
Saxton E.; Burns R.; Holveck S.; Kelley S.; Prince D.; Rigelman N. & Skinner E.A.	2014	A Common Measurement System for K-12 STEM education: Adopting an educational evaluation methodology that elevates theoretical foundations and systems thinking	2,4,5
Sergis S.; Sampson D.G.; Rodríguez-Triana M.J.; Gillet D.; Pelliccione L. & de Jong T.	2019	Using educational data from teaching and learning to inform teachers' reflective educational design in inquiry-based STEM education	3,4,5
Sheffield R.; Koul R.; Blackley S. & Maynard N.	2017	Makerspace in STEM for girls: a physical space to develop twenty-first-century skills	2,3
Stohlmann, M., Moore, T. J., & Roehrig, G. H.	2012	Considerations for teaching integrated STEM education	1,4
Thibaut L.; Knipprath H.; Dehaene W. & Depaepe F.	2018a	The influence of teachers' attitudes and school context on instructional practices in integrated STEM education	1,2,3,4
Thibaut L.; Knipprath H.; Dehaene W. & Depaepe, F.	2019	Teachers' Attitudes Toward Teaching Integrated STEM: The Impact of Personal Background Characteristics and School Context	1,4

Author(s)	Year	Title of Publication	RQ
Thomas B. & Watters J.J.	2015	Perspectives on Australian, Indian and Malaysian approaches to STEM education	3,4
Vickrey T.; Rosploch K.; Rahmanian R.; Pilarz M. & Stains M.	2015	Research-Based Implementation of Peer Instruction: A Literature Review	4
Walan S. & McEwen B.	2018	Teachers' and principals' reflections on student participation in a school science and technology competition	2,4
Weintrop D.; Beheshti E.; Horn M.; Orton K.; Jona K.; Trouille L. & Wilensky U.	2016	Defining Computational Thinking for Mathematics and Science Classrooms	3,5
Yanez G.A.; Thumlert K.; de Castell S. & Jenson J.	2019	Pathways to sustainable futures: A "production pedagogy" model for STEM education	4
Zhou S.; Zeng H.; Xu S.; Chen L. & Xiao H.	2019	Exploring Changes in Primary Students' Attitudes Towards Science, Technology, Engineering, and Mathematics (STEM) Across Genders and Grade Levels	3,5

Follow Up Search of the Literature

Based on the review of these 54 publications, the phrase "Integrated STEM Education" emerged as a strong indicator of relevant studies on STEM education. Therefore, a follow-up literature search was carried out in Scopus for the period 2010-2019, using the keyword search term "Integrated STEM Education" and applying the same exclusion criteria. The application of the review criteria resulted in 56 studies on the basis of the titles and abstracts of these publications. After close analysis, 16 of these studies were disqualified due to overlapping with the first review. The remaining 40 studies were further reviewed by reading the entire paper to ensure that they addressed "Integrated STEM education" in the school context and involved all four STEM disciplines, rather than targeting only one or two of them. As a result, both researchers were in full agreement that 19 out of 40 studies were disqualified due to one or more of these reasons. Table 6 presents the reasons for disqualifying these 35 publications from the review.

Table 6: Reasons for disqualifying 35 additional studies identified in the second review

Number of Studies	Description	Reason
15	These 14 publications were already included in 54 studies selected in the first review.	First search
1	Included in the 312 studies for the first review but disqualified due to targeting a different focus.	First search
5	Disqualified due to having a different focus.	Second search
5	Disqualified due to not being able to access the full publication.	Second search
8	Disqualified due to not being a paper, book or book chapter (i.e. some results were only a conference name).	Second search
1	Disqualified as it was an unfinished paper.	Second search

The remaining 21 publications identified as relevant for inclusion in this review, are outlined in Table 7.

Table 7: Overview of the 21 additional publications identified as relevant for inclusion

Author(s)	Year	Title of Publication	RQ
Aydin-Gunbatar S., Tarkin-Celikkiran A., Kutucu E.S. & Ekiz-Kiran B.	2018	The influence of a design-based elective STEM course on pre-service chemistry teachers' content knowledge, STEM conceptions, and engineering views	1,4
Bartholomew S.R., Moon C., Ruesch E.Y. & Strimel G.J.	2019	Kindergarten student's approaches to resolving open-ended design tasks	3,5
Dan Z.S. & Gary W.K.W.	2018	Teachers' perceptions of professional development in integrated STEM education in primary schools	4
Eguchi A. & Uribe L.	2017	Robotics to promote STEM learning: Educational robotics unit for 4th grade science	2,3,5
English, L.D.	2016	STEM education K-12: perspectives on integration	2,3
Guzey S.S. & Moore T.J.	2015	Assessment of curricular materials for integrated STEM Education (RTP, Strand 4)	4,5
Guzey S.S., Moore T.J. & Harwell M.	2016	Building up stem: An analysis of teacher-developed engineering design-based stem integration curricular materials	2,4,5
Honey M.A., Pearson G. & Schweingruber H.	2014	STEM integration in K-12 education: status, prospects, and an agenda for research	1,2,3
Mohd Shahali E.H., Halim L., Rasul M.S., Osman K. & Zulkifeli M.A.	2017	STEM learning through engineering design: Impact on middle secondary students' interest towards STEM	1,3
Mohd Shahali E.H., Halim L., Rasul, S., Osman K., Ikhsan Z. & Rahim F.	2015	Bitara-Stem™ training of trainers' programme: Impact on trainers' knowledge, beliefs, attitudes and efficacy towards integrated stem teaching	2,4
Nathan M. & Pearson G.	2014	Integration in K-12 STEM education: Status, prospects, and an agenda for research	1,4
Pearson, G.	2017	National academies piece on integrated STEM	3
Rippon S. & Collofello J.	2012	Engineers Serving Education: Bringing math and science to life in the K-8 classroom	3,4
Shahbazi Z., Jacobs M., Lehnes A. & Mancuso K.	2016	Designing integrated STEM education: Linking STEM teachers and learners in a k-20 continuum	3,4
Shernoff D.J., Sinha S., Bressler D.M. & Ginsburg L.	2017	Assessing teacher education and professional development needs for the implementation of integrated approaches to STEM education	4
Struyf A., De Loof H., Boeve-de Pauw J. & Van Petegem P.	2019	Students' engagement in different STEM learning environments: integrated STEM education as promising practice?	1,2,3

Author(s)	Year	Title of Publication	RQ
Subbian, V.	2013	Role of MOOCs in integrated STEM education: A learning perspective	3,5
Thibaut L., Knipprath H., Dehaene W. & Depaepe F.	2018b	How school context and personal factors relate to teachers' attitudes toward teaching integrated STEM	1,4
Türk N., Kalaycı N. & Yamak H.	2018	New trends in higher education in the globalizing world: STEM in teacher education	2,4
Wong G.K.W. & Huen J.H.M.	2017	A conceptual model of integrated STEM education in K-12	1,2,3
Wong, G.K.W.	2017	Integrative learning in K-12 STEM education: How to prepare the first step?	1,2,3

Four further studies were idenitied as relevant to addressing the research questions of this study are included in Table 8. These four articles had been cited in some of the 54 selected publications listed in Table 5.

Table 8: Four publications selected from citations from the list of 54 selected publications

Author(s)	Year	Title of Publication	RQ
Wang H.; Moore T.J.; Roehrig, G.H. & Park M.S.	2011	STEM Integration: Teacher Perceptions and Practice	1,2,3,4
Shaughnessy M.	2013	Mathematics in a STEM Context	1
Moore T.J. & Smith K.A.	2014	Advancing the State of the Art of STEM Integration	1,3,4
Thibaut, L., Ceuppens, S., De Loof, H., De Meester, J., Goovaerts, L., Struyf, A., Boeve-de Pauw, J., Dehaene, W., Deprez, J., De Cock, M., Hellinckx, L., Knipprath, H., Langie, G., Struyven, K., Van de Velde, D., Van Petegem, P. and Depaepe, F.	2018	Integrated STEM Education: A Systematic Review of Instructional Practices in Secondary Education	2,3,4

Figure 5 illustrates the stages of the review process and use of exclusion criteria for the two different searches. A full list of the 79 publications included in this review of STEM Education is presented in Appendix C.

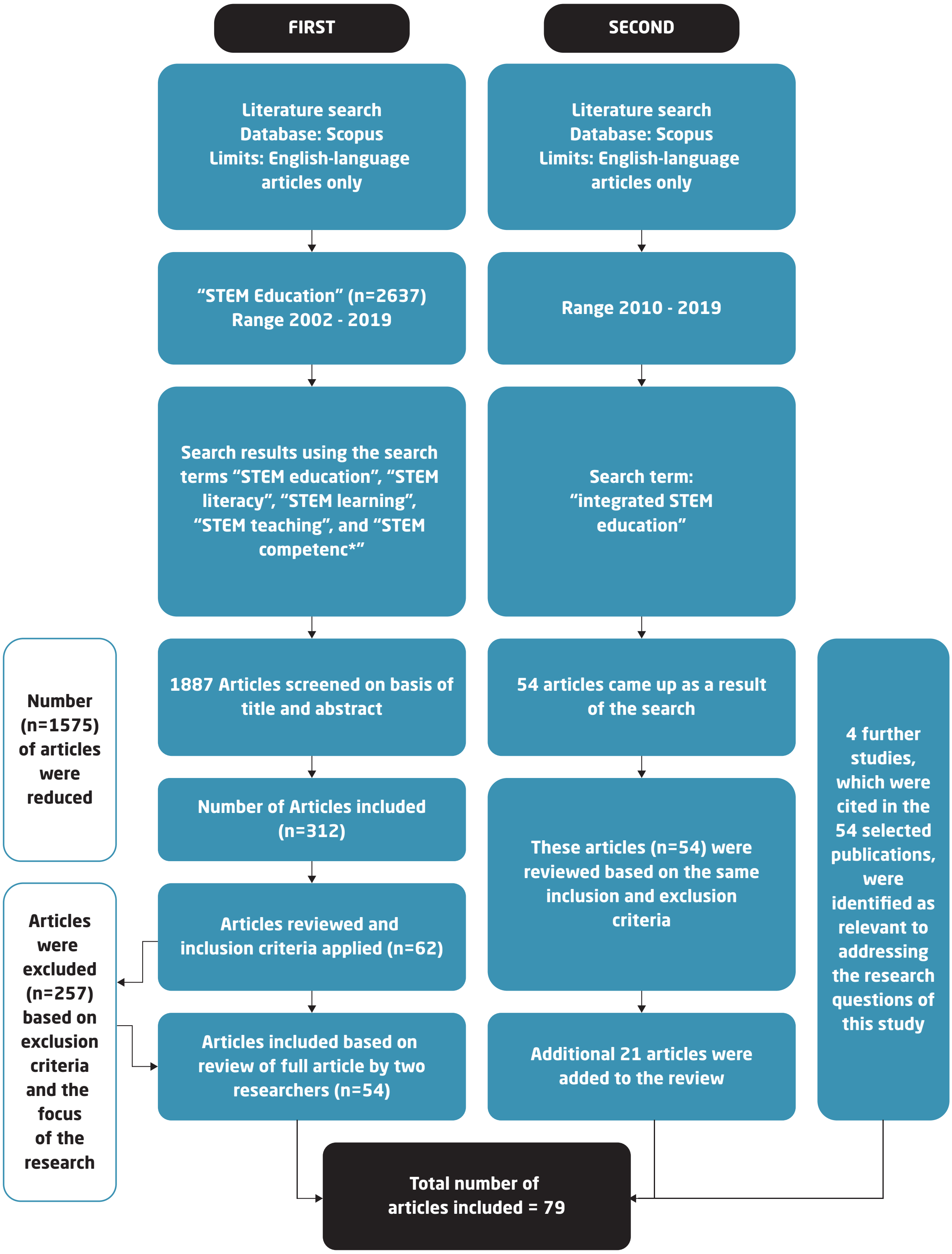


Figure 5: Overview of the stages of the review process and use of exclusion criteria in first and second review

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EMERGENT THEMES

This section presents the major findings and emergent themes arising from a synthesis of the literature. It describes the findings to be as accessible and comprehensible as possible to each of the target stakeholders, including students, teachers, parents, policymakers, higher educators, and those involved in industries concerned with STEM education. The key takeaways for all stakeholders are presented in highlight boxes throughout the report to underscore their significance for the reader. As mentioned in the methodology, this section presents the findings in terms of five key areas of investigation:

1. Defining and conceptualising STEM education,
2. Core STEM competences,
3. Integrated STEM curriculum and its "real-world" practical applications,
4. STEM education in teacher education,
5. Assessment in STEM education.

The literature pertinent to each key area is outlined and discussed in the following five subsections.

Defining and Conceptualising STEM Education

This section aims to help define and conceptualise STEM education. The purpose of the section is to explore different definitions of STEM education and more specifically in the context of this project, identify the key characteristics of integrated STEM education.

Why do we need a common definition of STEM education?

The literature review reveals a varied and diverse range of research (and related definitions) on STEM education across numerous countries and this lack of consensus in a common definition presents many challenges for both educators and policymakers (See, for example, Martin-Paez et al., 2019; Thomas & Watters, 2015). European Schoolnet (2018) highlights the need to develop a common definition and understanding of what STEM education implies, so as to:

1. To attract more students and teachers to STEM education through a global approach from primary to adult education that will better anticipate the skills needed for the society of the future;
2. To break down the barriers between subjects with pragmatic initiatives (teacher training sessions, publish content, share best practices, etc.) to improve the quality of STEM education by building on each country's strengths;
3. To foster deeper collaboration with universities and industry to develop STEM teachers' skills;
4. To evaluate and integrate curriculum and pedagogical innovations: all energies must be oriented in the right direction with value-added purpose-built technologies and services that need to be provided; positive experimentations need to be rolled out across the entire education system and disseminated among European countries (sharing of best practices, ideally in line with a common European framework);
5. To develop a common European framework of reference for STEM education and coordinating national STEM initiatives related to publishing pedagogical content to ensure teachers' needs are being met.

The key challenge highlighted above is the need to develop a common European framework of reference for STEM education (European Schoolnet, 2018). Doing this is central to enabling us to tackle the other challenges. Having a common frame of reference, coupled with a shared meta-language for describing STEM, would be a first step in helping "better anticipate the skills needed for the society of the future", "foster deeper collaborations with universities and industry", evaluating "pedagogical innovations" and breaking "down the barriers between subjects" to "attract more students and teachers for STEM education". However, to do this effectively, there is an urgent need to interrogate and unpack the term STEM education, and to develop an understanding of what we mean by STEM education. Therefore, drawing on our analysis of the literature, this section discusses the need for more agreed and explicit definitions of STEM education. Building on this discussion, we will identify the key characteristics arising from the literature in different STEM definitions, which will provide a foundation for the following sections.

What are the different definitions of STEM education?

It is difficult to understand STEM education due to inconsistent language and a lack of definition of terms (Martin-Paez et al., 2019). What is evident from the literature is the range and scope of what is defined as STEM education (e.g. Bybee, 2013; Hodges et al., 2016; Martin-Paez et al., 2019; Moore & Smith, 2014; Moore et al., 2016; Shaughnessy, 2013). As stated by European Schoolnet (European Schoolnet, 2018), there is a need for a common European framework; however, there is no consensus on the definition of STEM education to use for developing this framework (Bybee, 2013).

Definitions of STEM range from simple referencing of the four STEM disciplines; educational approaches at the intersections of any number of the four disciplines; to referencing all four STEM disciplines in an integrated manner (Bybee, 2013; Sanders 2009). Martin-Paez et al. (2019) conducted a review to examine how STEM education is implemented in the published literature and analysed theoretical frameworks of the interventions. They found that 55% of the studies selected (n = 16) failed to explain and define STEM concepts in their theoretical frameworks. Similarly, the results of our systematic search for this literature review demonstrated that 55 out of 79 publications (70%) did not actually explain what they mean by STEM education. Publications that did attempt to describe or define STEM education and that cited other definitions in doing so are categorised and presented in this section. What emerged from the literature was a set of core definitions, outlined in Table 9 that tended to be adopted and adapted by researchers in the period 2011-2019.

Table 9: Definitions of the STEM education reported in literature (2011-2019)

Definition	Further Definition	Defined By	Adopted By
STEM integration in the classroom is a type of curriculum integration. The concept of curriculum integration is complex and challenging, as integration of subjects is more than a matter of simply putting different subject areas together.		Wang H.; Moore T.J.; Roehrig, G.H. and Park M.S. (2011 p.2)	Mohd Shahali et al. (2017), Ryu, Mentzer and Knobloch (2019)
Integrated STEM education is an effort to combine science, technology, engineering, and mathematics into one class that is based on connections between the subjects and real world problems.		Stohlmann, M., Moore, T. J., and Roehrig, G. H. (2012, p.30)	
STEM education should include the application of knowledge, skills, and abilities to real-life situations, such as to health choices and environmental quality.	The author argues the need for transcending the traditional boundaries of STEM disciplines.	Bybee (2013)	
STEM is an instructional approach, which integrates the teaching of science and mathematics disciplines through the infusion of the practices of scientific inquiry, technological and engineering design, mathematical analysis, and 21st century interdisciplinary themes and skills		Johnson (2013, p.367)	
STEM education refers to solving problems that draw on concepts and procedures from mathematics and science while incorporating the team work and design methodology of engineering and using appropriate technology.		Shaughnessy (2013, p. 324)	Lesseig, Slavit and Nelson (2017)
STEM integration means working in the context of complex phenomena or situations on tasks that require students to use knowledge and skills from multiple disciplines.		Honey et al. (2014, p.52)	

Definition	Further Definition	Defined By	Adopted By
Integrated STEM education is an effort to combine the four disciplines of science, technology, engineering, and mathematics into one class, unit, or lesson that is based on connections among these disciplines and real-world problems.	STEM education is an instructional approach in which students participate in engineering design and/or research and experience meaningful learning through integration and application of mathematics, technology and/or science.	Moore and Smith (2014, p.5)	Thibaut L.; Knipprath H.; Dehaene W. and Depaepe F. (2018a, p.190; 2019, p.989)
The authors of this study operationalize the definition of STEM learning by extending the definition of learning. STEM learning is the acquisition of knowledge and skills through experience and study integrated though multiple lens allowing for the appreciation of the encompassing complexity and cross-cutting ideas across the STEM disciplines as a whole.		Lamb et al. (2015, pp. 410-411)	
STEM education is the teaching and learning of the content and practices of disciplinary knowledge which include science and/or mathematics through the integration of the practices of engineering and engineering design of relevant technologies.	Authors mention the importance of making connections between the subjects and real-world problems when integrating STEM education.	Moore T.J.; Johnson C.C.; Peters-Burton E.E. & Guzey S.S. (2016, p. 23)	Radloff and Guzey (2016), Aydin-Gunbatar et al. (2018)
The integrated of STEM education can be defined as incorporating the theory and practices of science and mathematics education into technology and engineering education.		Mustafa, Ismail, Tasir & Mohamad Said (2016)	
STEM is an integrated, interdisciplinary approach to learning that provides hands-on and relevant learning experiences for students. ... It engages students and equips them with critical thinking, problem solving, creative and collaborative skills, and ultimately establishes connections between the school, work place, community and the global economy.	Then, the definition was narrowed down as "an integrated curriculum (as opposed to science, technology, engineering, and mathematics taught in isolation) that is driven by problem solving, discovery, exploratory project/problem-based learning, and student-centred development of ideas and solutions".	Hodges et al. (2016, p.200)	

Definition	Further Definition	Defined By	Adopted By
STEM education is the approach to teaching the STEM content of two or more STEM domains, bound by STEM practices within an authentic context for the purpose of connecting these subjects to enhance student learning		Kelley and Knowles (2016, p.3)	Wong (2017)
Integrated STEM education refers to the intentional engagement with products or solving real world problems that requires utilising two or more of the STEM disciplines, with or without other discipline areas such as the Arts, in tandem with 21st century competences – adaptability, communication, social skills (collaboration), creativity, non-routine problem solving, self- management, self-development and systems thinking.		Blackley S. and Howell J. (2019, p.56)	
STEM education is a teaching approach that integrates content and skills specific to science, technology, engineering, and mathematics.	Authors advocate the unification of terms and the adoption of STEM education visions that converge into a simultaneous study of the four STEM disciplines without losing their essence.	Martin-Paez et al. (2019, p. 815)	
Integrated STEM requires the application of knowledge and practices from various STEM disciplines to solve complex and transdisciplinary problems		Struyf A.; De Loof H.; Boeve-de Pauw J. & Van Petegem P. (2019)	

Table 10: Characteristics of STEM education as identified in 20 publications (2010-2019)

Characteristics	Sub-characteristics	Stohlmann et al. (2012)	Bybee (2013)	Johnson (2013)	Shaughnessy (2013)	Honey et al. (2014)	Lamb et al. (2015)	Moore and Smith (2014)	Moore et al. (2016)	Mustafa et al. (2016)	Hodges et al. (2016)	Kelley and Knowles (2016)	Lesseig et al. (2017)	Radloff and Guzey (2016)	Wong (2017)	Aydin-Gunbatar et al. (2018)	Thibaut et al. (2018a, 2019)	Thibaut et al. (2018b)	Blackley and Howell (2019)	Martin-Paez et al. (2019)	Struyf et al. (2019)
Core STEM Competences	Skills/abilities from multiple disciplines (including 21st century skills)		X	X		X	X				X								X	X	
	Team work				X								X								
	Mathematical analysis			X																	
Problem-Solving Design and Approaches	Problem-solving	X			X			X			X		X				X	X	X		X
Disciplinary and Interdisciplinary knowledge	Knowledge from multiple disciplines		X			X	X													X	X
	Cross-cutting ideas across the STEM disciplines						X														
	Transdisciplinary problems																				X

Characteristics	Sub-characteristics	Stohlmann et al. (2012)	Bybee (2013)	Johnson (2013)	Shaughnessy (2013)	Honey et al. (2014)	Lamb et al. (2015)	Moore and Smith (2014)	Moore et al. (2016)	Mustafa et al. (2016)	Hodges et al. (2016)	Kelley and Knowles (2016)	Lesseig et al. (2017)	Radloff and Guzey (2016)	Wong (2017)	Aydin-Gunbatar et al. (2018)	Thibaut et al. (2018a, 2019)	Thibaut et al. (2018b)	Blackley and Howell (2019)	Martin-Paez et al. (2019)	Struyf et al. (2019)
Engineering Design and Practices	Engineering design/practices			X	X				X				X	X		X	X	X			
Appropriate Use and Application of Technology	The use and application of technology tools and technology background			X	X				X				X	X		X					
Use of Real-World Contexts	Real-life/ world	X	X					X									X	X	X		
	The context of complex phenomena or situations					X	X														X
	An authentic context											X			X						
	Intentional engagement with products																		X		
	Connecting the school, work place, community and the global economy										X										

Characteristics	Sub-characteristics	Stohlmann et al. (2012)	Bybee (2013)	Johnson (2013)	Shaughnessy (2013)	Honey et al. (2014)	Lamb et al. (2015)	Moore and Smith (2014)	Moore et al. (2016)	Mustafa et al. (2016)	Hodges et al. (2016)	Kelley and Knowles (2016)	Lesseig et al. (2017)	Radloff and Guzey (2016)	Wong (2017)	Aydin-Gunbatar et al. (2018)	Thibaut et al. (2018a, 2019)	Thibaut et al. (2018b)	Blackley and Howell (2019)	Martin-Paez et al. (2019)	Struyf et al. (2019)
Appropriate Pedagogical Practices	Combining STEM into one class/ activity	X					X	X									X	X			
	An instructional approach			X													X				
	Incorporating the theory and practices									X		X			X						
	STEM practices											X			X						X
	Research and experience																X	X			
	The practices of scientific inquiry			X																	
	Hands-on and relevant learning experiences										X										
	Discovery, exploratory project/problem-based learning										X										
	Student-centred										X										

Analysing 23 sub-characteristics (Table 10) further, we have identified seven characteristics of integrated STEM education as presented in Table 11.

Table 11: Seven characteristics of integrated STEM education

	Seven Characteristics of Integrated STEM Education
1	Core STEM Competences
2	Problem-Solving Design and Approaches
3	Disciplinary and Interdisciplinary Knowledge
4	Engineering Design and Practices
5	Appropriate Use and Application of Technology
6	Use of Real-World Contexts
7	Appropriate Pedagogical Practices

The next section will discuss in detail what core STEM competences have been identified and presented in the literature. The other six characteristics are combined to articulate the STEM Learning Design Principles element of the ATS STEM Framework, which is presented in Report #5 of the ATS STEM report series.

Core STEM Competences

The set of knowledge, skills and/or competences an individual has acquired and/or is able to demonstrate after completion of a learning process. Learning outcomes are statements of what a learner is expected to know, understand and/or be able to do at the end of a period of learning *(ENCoRE, 2005, p.11)*

The concerns about what students need to learn for successful future lives has been a major focus of national and international policymakers over the past two decades (e.g. Griffin & Care, 2010; European Commission, 2007, 2019; OECD, 2018). National curriculum authorities in many countries have begun to embrace broader learning goals to include knowledge, skills, competenc(i)es, attitudes, values and ethics. In recent years, the term 'skill'– as in 21st century skills – has been prevalent, but more recently there has been the emergence of key 'competencies' or 'competences' which are required for a successful life and well-functioning society.

It is important to highlight what is the current understanding of the concepts of skills, competences, and competencies. Being skillful generally refers to carrying out some action with a degree of proficiency, doing it well rather than poorly - implying that there are degrees of skillfulness and that skills can be learned and improved. However, using the term skills or even key skills can often be interpreted as reductionistic and not fully capturing what it is meant to carry out these actions well (McGuinness, 2018, p.9). Consequently, the terms, "competences" and "competencies" are more prevalent in describing what is required to live, thrive, and flourish in a complex, connected society.

".. a competency is more than just knowledge and skills. It involves the ability to meet complex demands, by drawing on and mobilising psychosocial resources (including skills and attitudes) in a particular context. *(OECD, 2005, p. 4)*

At an international level, for example, both the OECD (OECD, 2018) and the International Bureau of Education/UNESCO (Marope et al., 2017) have groups working on how best to conceptualise key competenc(i)es in curriculum frameworks. Although key competenc(i)es are often substituted for key skills, they do have different meanings, specifically in terms of their focus on (1) the action in response to the demands of a situation, and (2) the inclusion of knowledge as a key component that informs the action. According to OECD's DeSeCo definition, a competency includes - prior knowledge relating to the context, cognitive skills, practical skills, social skills, emotions, attitudes, values— co-ordinated to enable the person to act in relation to a specific demand (Rychen & Salganik, 2003).

> *".. a competency is more than just knowledge and skills. It involves the ability to meet complex demands, by drawing on and mobilising psychosocial resources (including skills and attitudes) in a particular context. For example, the ability to communicate effectively is a competency that may draw on an individual's knowledge of language, practical IT skills and attitudes towards those with whom he or she is communicating" (OECD, 2005 p. 4).*

In Europe, detailed work has been carried out to formulate the types of learning outcomes that would be appropriate in a European Qualifications Framework (EQF) (ENCoRE, 2005), with the qualifications at each level of the framework described in terms of three types of learning outcomes:

- knowledge;
- skills; and
- wider competences described as personal and professional outcomes.

Competence can be seen as the ability of an individual to use and combine his or her knowledge, skills and wider competences according to the varying requirements posed by a particular context, a situation or a problem *(ENCoRE, 2005, p.11).*

The concept of competences, as defined in Table 2, is used in an integrative manner; as an expression of the ability of individuals to combine - in a self-directed way, tacitly or explicitly and in a particular context - the different elements of knowledge and skills they possess. The aspect of self-direction is critical to the concept as this provides a basis for distinguishing between different levels of competences. Acquiring a certain level of competence can be seen as the ability of an individual to use and combine his or her knowledge, skills and wider competences according to the varying requirements posed by a particular context, a situation or a problem (ENCoRE, 2005, p.11).

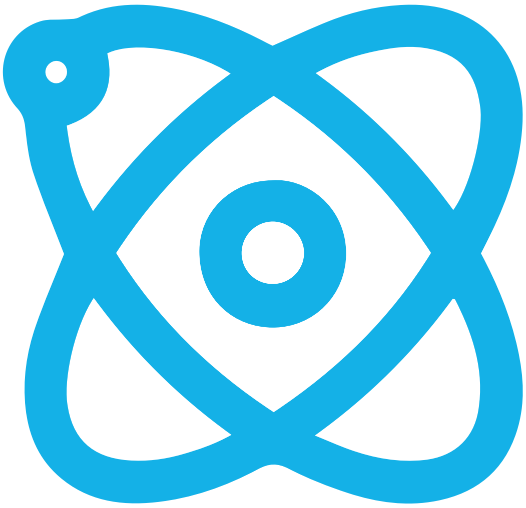

Table 12: Definition of a Competence proposed for a European Qualifications Framework (ENCoRE, 2005, p.11)

Competences include:

i) cognitive competence involving the use of theory and concepts, as well as informal tacit knowledge gained experientially;

ii) functional competence (skills or know-how), those things that a person should be able to do when they are functioning in a given area of work, learning or social activity;

iii) personal competence involving knowing how to conduct oneself in a specific situation; and

iv) ethical competence involving the possession of certain personal and professional values

While both examples discussed above make use of different terms (competencies or competences) to capture the complexity of what is required, the critical point is that there is a high degree of commonality and for both the emphasis is more on what to do with the knowledge rather than on the knowledge itself. In writing this report, a choice had to be made in relation to using the term Competencies or Competences. Respecting the choice that has been made in all European publications to date on the topic, for consistency and coherence, the term "Competences" will be used.

As noted in Report #1, the analysis of the literature identified 243 specific STEM skills and competenc(i)es. We classified these 243 specific STEM skills and competenc(i)es into eight categories and collectively define them as Core STEM Competences in the ATS STEM Conceptual Framework and are depicted in Table 13.

Table 13: Eight Core STEM Competences

	Eight Core STEM Competences
1	Problem-Solving
2	Innovation and Creativity
3	Communication
4	Critical Thinking
5	Meta-Cognitive Skills
6	Collaboration
7	Self-Regulation
8	Disciplinary Competences

We consider the opportunity to develop these eight core competences essential in STEM education because of their cross-cutting and transversal nature – i.e. that they cut across different domains of STEM and are useful across a range of different contexts throughout life. These eight Core STEM Competences are presented and expanded upon with their sub-categories in Table 14 (See Appendix D for the complete list of specific STEM skills and competences highlighted by each author). A summary of the different categories of STEM skills and competences found in each publication is illustrated in Table 15 and is discussed in more detail below.

Table 14: Core STEM Competences in STEM education

Core STEM Competences	Specific Skills and Competences	
Problem-solving	Problem-solving	Making judgements
	Decision-making	Research
	Inquiry	Inference making
	Complex problem solving	Hypotheses making
	Algorithmic problem solving	Seeking evidence
	Non-routine problem solving	Dealing with information
	Creative problem-solving skills	Asking questions and gathering information to solve problems
Innovation and Creativity	Innovation (innovative thinking)	Entrepreneurship
	Taking an initiative	Making an invention
	Coming up with new ideas	Creativity
Communication	Communication	Presenting
Critical Thinking	Reflective thinking skills	Logical reasoning
	Critical thinking	Associative thinking
	High order thinking skills	Convergent thinking
	Logical thinking	Divergent thinking
	Reasoning	Analytical thinking
	Critical reasoning	Argumentation
Meta-Cognitive Skills	Adaptability	Cognitive and meta- cognitive skills
	Systems thinking	Making connections with learning experiences
	Flexibility	
Collaboration	Collaborative skills	Attentiveness
	Teamwor	Courtesy
	interpersonal attributes	personal skills
	Leadership	Intrapersonal traits
	Cooperative thinking	Talking to others
	Team building	Listening to others
	Negotiation skills	Working with others
	Conflict resolution	Social and cultural skills
	Mutual respect	Being sensitive to others' feelings
	Ethical awareness	

Core STEM Competences	Specific Skills and Competences	
Self-Regulation	Responsibility	Perseverance
	Self-management	Positive attitude
	Being on time	Autonomous learning
	Self-control	Working on their own
	Self-development	Integrity
	Self-confidence	Sustainability and Social commitment
	Self-discipline	Career and life skills
	Appropriate attitude towards work	Not giving up on a task that is too hard to finish
	Dependability	Persistence
	Trustworthiness	Always doing what you said you were going to do
	Motivation	
Disciplinary Competences	Theoretical learning	Computer skills
	Practical skills	Computing (computational) skills
	Engineering skills	Information literacy
	Engineering design skills	Technology literacy
	Mathematical (thinking) skills	Technological skills
	Numeracy skills	Digital literacy (e.g. writing code/ analysing data)
	Solving math problems	Digital technology skills
	Scientific skills	Programming skills
	Testing ideas about science	Express themselves using the technological tool
	Conducting science labs/ experiments	

Table 15: Overview of core STEM competences in STEM education as identified by authors

Authors	Problem-Solving	Innovation and Creativity	Communication	Critical Thinking	Meta-Cognitive Skills	Collaboration	Self-Regulation	Disciplinary Competences
Wang et al. (2011)	x			x	x			x
Bybee (2013)	x		x		x		x	
Honey et al (2014)		x	x	x	x	x		x
Saxton et al. (2014)				x	x			x
Kim et al. (2015)	x	x	x	x		x		x
Mustafa et al. (2016)	x		x	x		x		
Mohd Shahali et al. (2015)		x	x					
English (2016)	x	x		x				
Guzey et al. (2016)			x			x		x
Hodges et al. (2016)	x	x		x		x		
Eguchi and Uribe (2017)	x	x	x	x		x		x
EL-Deghaidy et al. (2017)	x	x		x	x	x		
Lesseig et al. (2017)	x	x	x	x		x		
Sheffield et al. (2017)	x	x	x	x		x		
Wong (2017)	x				x	x	x	
Wong & Huen (2017)		x	x	x				x
Sánchez Carracedo et al. (2018)	x	x	x	x		x	x	x
Sarican & Akgunduz (2018)	x	x	x	x	x	x	x	x
Thibbaut et al. (2018)	x	x	x	x		x		
Thibaut et al. (2018a)	x	x	x	x		x		
Türk et al. (2018)	x	x	x	x		x		
Walan & McEwen (2018)	x	x	x	x		x		
Blackley & Howell (2019)	x	x	x	x	x	x	x	x
Jagannathan et al. (2019)	x	x	x			x	x	x
Kurup et al. (2019)	x	x	x	x		x		x
Martin-Paez et al. (2019)	x	x		x		x		x
Struyf et al. (2019)	x	x		x		x		

A brief overview of each of these core competences which comprise the first component of the ATS STEM Conceptual Framework is outlined below.

Collaboration

In today's connected complex world simply knowing some facts in a single domain and/or how to use tools is not enough for individuals to stay effective and competitive. Consequently, there is an increasing emphasis in literature on the importance of learning to work collaboratively and productively with others in groups for participating effectively in society (Eguchi & Uribe, 2017). It is not surprising then that "Collaboration" was the most frequently mentioned core STEM competency (n=44) of literature referring to integrated STEM education.

Collaboration refers to working with someone to produce something and it can be linked to or have an impact on other skills and competences.

Collaboration refers to working with someone to produce something and it can be linked to or have an impact on other skills and competences. Collaboration can be between students, students and teachers, teachers, teachers and universities, universities and industries (Honey et al., 2014). Peer collaboration can help students be successful with challenging tasks and move beyond their current state of knowledge (Honey et al., 2014).

Furthermore, working collaboratively and team learning, in a spirit of co-creation, enhance key competences essential for the 21st century and can lead to benefits that are greater than the sum derived from the constituent parts, which can support people becoming enthusiastic promoters of inquiry-oriented learning and portraying positive views of science (European Commission, 2015). Robotics was utilised in some studies to develop collaborative working. For example, Kim et al. (2015) used collaborative small group activities to develop a robot, which resulted in the improvement of collaborative and communicative skills. The European Commission (2019) highlights the role and importance of collaboration of learners within digital competence, personal, social and learning to learn competence, entrepreneurship competence. For example, supporting active citizenship and social inclusion and collaboration with others can be achieved by using digital technologies (European Commission, 2019). The European Commission supports applying collaboration in digital technologies in two different ways: (1) to foster and enhance learner collaboration, and (2) to facilitate learners' digital competence through digital communication and collaboration (European Commission, 2015). Some example activities suggested by the European Commission (2015) are as follows:

- To implement collaborative learning activities in which digital devices, resources or digital information strategies are used.
- To implement collaborative learning activities in a digital environment, e.g. using blogs, wikis, learning management systems.
- To employ digital technologies for collaborative knowledge exchange among learners.
- To monitor and guide learners in their collaborative knowledge generation in digital environments.
- To require learners to digitally present their collaborative efforts and assist them in doing so.
- To use digital technologies for peer-assessment and as a support for collaborative self-regulation and peer-learning.
- To use digital technologies to experiment with new formats and methods for collaborative learning.

Problem-Solving

The second most frequently identified core STEM competences (n=42) of integrated STEM education was "problem-solving". Problem-solving can be defined as the process of finding solutions to difficult or complex issues. Many authors stated that STEM curricula should provide student experiences that include problem-solving activities and support students in developing this competency. Wang et al. (2011) analysed different STEM programs and curricula designs and found that many researchers and educators agreed on two major foci of STEM integration: (1) problem solving through developing solutions and (2) inquiry. STEM curricula should not only focus on content knowledge but also needs to include the development of problem-solving skills and inquiry-based instruction. STEM curricula can be organised around problems and issues that are of personal and social significance in the real world. Adopting such an approach not only develops students' problem-solving skills it helps integrate meaningful content and leverages their ability to contextualise concepts to real-life situations (European Schoolnet, 2018; Hodges et al., 2016).

In today's connected world, digital problem-solving is promoted by the European Commission (Redecker, 2017). Digital problem-solving refers to the incorporation of learning activities, assignments and assessments which require learners to identify and solve technical problems, or to transfer technological knowledge creatively to new situations (Redecker, 2017). The importance of the development of such problem-solving skills is evident in European policy as demonstrated in the DigiComp Framework (Carretero, Vuorikari & Punie, 2017; Redecker, 2017).

Evidence arising from literature suggests that problem-solving can also help develop digital competence, citizenship competence, and entrepreneurship competence (European Commission, 2019). A good level of literacy, numeracy, and problem-solving skills in technology-rich environments is the key that allows people to unlock all the benefits of internet use and enables them to use technology in diversified and complex ways rather than just for information retrieval and simple communication (OECD, 2019). For example, a problem-solving attitude supports both the learning process and the individual's ability to handle obstacles and change. It includes the desire to apply prior learning and life experiences and the curiosity to look for opportunities to learn and develop in a variety of life contexts (European Commission, 2019). In addition, the European Commission (2019) claims problem-solving can help develop citizenship competence related to the ability to engage effectively with others in the common or public interest, including sustainable development of society.

Innovation and Creativity

The third most frequent core STEM competency identified in selected literature as being central to integrated STEM education was "creativity and innovation" (n=35). Creativity refers to coming up with a new idea by using imagination to either create something or make improvements in a current situation. Because creativity is a core competency that differentiates innovators from non-innovators, the learning environment matters (European Commission, 2015). Students of all ages should be inspired to be innovative and entrepreneurial in their approach to generating ideas and applying them to solving problems and to help develop sustainable responses to society's challenges (European Commission, 2015).

For example, competence in cultural awareness and expression involves having an understanding of and respect for how ideas and meanings are creatively expressed and communicated in different cultures and through a range of arts and other cultural forms (European Commission, 2019). Concerning digital competence, digital technologies can be used to support creativity with personal, social or commercial goals (European Commission, 2019). In schools, developing students' skills for a digital future can be achieved with the use of technology and this can foster innovative ways of teaching and mitigate school failure (OECD, 2019). As highlighted in the OECD's 'Going Digital and Future of Work' initiatives, close alignment is crucial between policies on education, the labour market, tax, housing, social protection, research, and innovation. An indicative action of innovation and creativity might be "projects and educational programmes that promote creativity, innovation and entrepreneurship throughout the educational life-cycle" (European Commission, 2015). There is also a consensus among stakeholders on the importance of STEM education to economic innovation (Kuenzi, 2008; OECD, 2010b). Therefore, one of the overarching goals of STEM education is to cultivate a new innovative generation.

Communication

"Communication" was one of the least referred to core STEM competency (n=20) in the literature. However, it is undeniable that communication is an inevitable part of our daily lives. It is not only an inescapable part of social relationships but also a significant part of work-life success, as employers rank highly the ability to communicate clearly and appropriately (Atkinson, 2012). Complex communications and social skills include skills in processing and interpreting both verbal and nonverbal information from others in order to respond appropriately (Bybee, 2013). A skilled communicator selects key pieces of a complex idea to express in words, sounds, and images as a way to build shared understanding. Skilled communicators negotiate positive outcomes with others through social perceptiveness, persuasion, negotiation, instructing, and service orientation (Bybee, 2013). The importance of being able to communicate skilfully cannot be underestimated. In fact, as our classrooms and workplaces become more ethnically, culturally and linguistically diverse, the ability to communicate across these diverse populations is paramount.

Communication can be defined as imparting or exchanging any type of information by processing and interpreting both verbal and nonverbal information from others to respond appropriately.

Bybee (2013)

Critical Thinking

"Critical thinking" was regularly referred to in the studies (n=35). Critical thinking can be defined as analysing and evaluating an issue objectively to make a judgement. For students in compulsory education, there is a range of initiatives on European, national and regional levels that offer guidelines and advice on how to enable young people to develop their digital competence, often with a focus on critical skills and digital citizenship (European Commission, 2017). For example, the European Commission (2017) recommended educators should develop activities that aim to critically reflect on one's own digital and pedagogic practice, and critically evaluate the credibility and reliability of digital sources and resources. In most European Member States, corresponding curricula have been or are being developed to ensure that the young generation is able to creatively, critically and productively take part in a digital society (European Commission, 2017). A focus on developing critical thinking can help develop other competences including, literacy competence, competence in science, technology and engineering, digital competence, personal, as well as social and learning competence (European Commission, 2019).

Hodges et al. (2016) conducted a case study exploring immersive learning environments, where students worked in pairs to execute a variety of tasks that assessed content understanding and the application of critical-thinking skills. The "Clark the Calf" case study is an interactive, three-dimensional, virtual learning environment, conceptualised by a team of veterinarians and science education researchers. In this immersive case study, students learn about osmosis while taking on the role of a health professional. They utilise problem-solving and critical-thinking skills that a scientist would use in real life to help save the calf. The importance of learning to think critically, to analyse and synthesise information in order to solve interdisciplinary problems, and to work collaboratively and productively with others in groups are important skills for participating effectively in society (Eguchi & Uribe, 2017). There is consensus in the integrated STEM education literature that it is no longer a case of simply knowing some facts in a single domain and/or how to use tools in order to stay effective and competitive in an increasingly complex society. How students think critically, how they can create something new are the things that are needed for the future (EL-Deghaidy et al., 2017).

The importance of learning to think critically, to analyse and synthesise information in order to solve interdisciplinary problems, and to work collaboratively and productively with others in groups are important skills for participating effectively in society.

Eguchi and Uribe (2017)

Self-Regulation

Self-regulation refers to self-management and self-development, which include personal skills needed to work remotely, in virtual teams; to work autonomously; and to be self-motivating and self-monitoring.

Bybee (2013)

“Self-regulation” was often identified as a core STEM competency (n=24). Self-regulation refers to self-management and self-development, which include personal skills needed to work remotely, in virtual teams; to work autonomously; and to be self-motivating and self-monitoring (Bybee, 2013). One aspect of self-management is the willingness and ability to acquire new information and skills (Houston, 2007). In addition, social and emotional skills, such as empathy, self-awareness, respect for others and the ability to communicate, are becoming essential as classrooms and workplaces become more ethnically, culturally and linguistically diverse. Achievement at school and beyond also depends on a number of social and emotional skills, such as perseverance, efficacy, responsibility, curiosity and emotional stability (OECD, 2019). Jagannathan et al. (2019) claims that these soft or “civic skills” (including perseverance, attentiveness, motivation, self-confidence, self-discipline, trustworthiness, and dependability) skills are developed early in a child’s life and are critical for success in school, the labour market, and life. Furthermore, these non-cognitive skills serve to promote the acquisition of cognitive skills early in a child’s development but the relationship does not appear to be reciprocal (Jagannathan et al., 2019).

Meta-Cognitive Skills

“Metacognitive skills” was the least referred to Core STEM competency (n=12). Metacognition is a subdivision of cognition, or a type of cognition. Metacognition is defined as the scientific study of an individual’s cognitions about his or her own cognitions. Cognition is a mental process that include memory, attention, producing and understanding language, reasoning, learning, problem-solving and decision making. It is often referred to as information processing, applying knowledge, and changing preferences. Flavell (1979; 1987) claims that metacognitive knowledge can be subdivided into three categories:

Metacognition is defined as the scientific study of an individual’s cognitions about his or her own cognitions.

1. Knowledge of Person variables- acquired knowledge and beliefs that concern what human beings are like as cognitive organisms
    - Intra-individual - knowledge or belief about intra-individual variation in one’s own or someone else’s interests
    - Inter-individual - compare between other people rather than within yourself
    - Universal - knowledge gained from maturation
2. Knowledge of Task variables- individual learns something about how the nature of the information encountered affects and constraints how one should deal with it (like how we get students to use their metacognition to study for a test)
3. Knowledge of Strategy variables- are cognitive strategies from getting here to there
    - Cognitive strategy - designed to get the individual to some cognitive goal or sub-goal
    - Metacognitive strategy - used to monitor cognitive strategies.

Saxton et al. (2014) advocate that students' higher order thinking or cognitive skills refer to their abilities concerning (1) problem-solving, (2) developing an argument based on evidence, (3) communicating ideas, and (4) utilising metacognitive skills. By metacognitive skills, Saxton et al. (2014) refer to the ability to reflect on one's own thinking and reasoning and choosing and strategically using tools (technological and otherwise). Cognitive and metacognitive skills also refer to system thinking which might be seen as a holistic approach to an activity by attempting to develop a system in an activity. For example, Blackley and Howell (2019) support system thinking as one of the 21st century skills and aim to design a system of a functioning robot. Design-based learning activities can be utilised to develop cognitive and metacognitive skills and competences, as it encourages flexibility and system thinking (e.g., Blackley & Howell 2019; Wong, 2017). The development of metacognitive skills needs to be given greater attention when one considers the role that metacognition and emotions play in a learners' ability to monitor and regulate their learning about 21st century skills. This is particularly relevant to science, technology, engineering, and mathematics (STEM) content involving the use of advanced learning technologies e.g., intelligent tutoring systems, serious games, hypermedia, augmented reality (Azevedo et al., 2017).

Disciplinary Competences

Another category of core STEM competency that emerged from the review of the literature was "Disciplinary Competences" (n=30), which relates to the disciplines of science, technology, engineering, and mathematics. Disciplinary competences refer to knowledge, skills and attitudes that are required by a specific STEM discipline. For example, programming languages may be required in the discipline of technology but less important in the discipline of science.

According to OECD (2010), innovation is a highly interactive and multidisciplinary process/ product that rarely occurs in isolation and is closely related to everyday life.

Disciplinary competences not only refers to each discipline in isolation but also the combination of these disciplines. Indeed, the European Commission (2019) considers STEM competences, which include knowledge, skills and attitudes of STEM disciplines, as one of the core lifelong learning competences. Designing learning experiences for students that engage them in authentic, real-world design challenges enables the development of the disciplinary knowledge and core skills across and between the integrated STEM disciplines (Moore & Smith 2014; Thibaut et al., 2019; Wang et al., 2011). Thus, STEM education should focus on innovation and the applied process of designing solutions to complex contextual problems using current tools and technologies (Kennedy & Odell, 2014).

Key Skills and Competences

What is significant to note is that there is considerable overlap with the eight core STEM competences that have been identified by this review and discussed in the previous sections, and the key skills and competences identified by international reports, e.g. European Commission and OECD (See Table 16). A range of key skills and competences have been identified as essential in order for every individual living in the member countries of EU and OECD to successfully flourish in life into the future and should not be considered as "extra" or "separate" from the curricular activities.

Table 16: Key skills and competences

Authors	Report Title	Key Skills And Competences
European Commission (2019)	Key Competences for Lifelong Learning	• Literacy competence • Multilingual competence • Mathematical competence and competence in science, technology and engineering • Digital competence • Personal, social and learning to learn competence • Citizenship competence • Entrepreneurship competence • Cultural awareness and expression competence
OECD (2019)	Transformative competences for all subjects	Key competences • creating new value • reconciling tensions and dilemmas • taking responsibility Key skills • cognitive and meta- cognitive skills • social and emotional skills • physical and practical skills

The OECD 2030 framework for education (See Figure 6) clearly illustrates how these knowledge, skills and attitudes/values combine to develop competences which are interrelated and can be translated into action by interacting with each other.

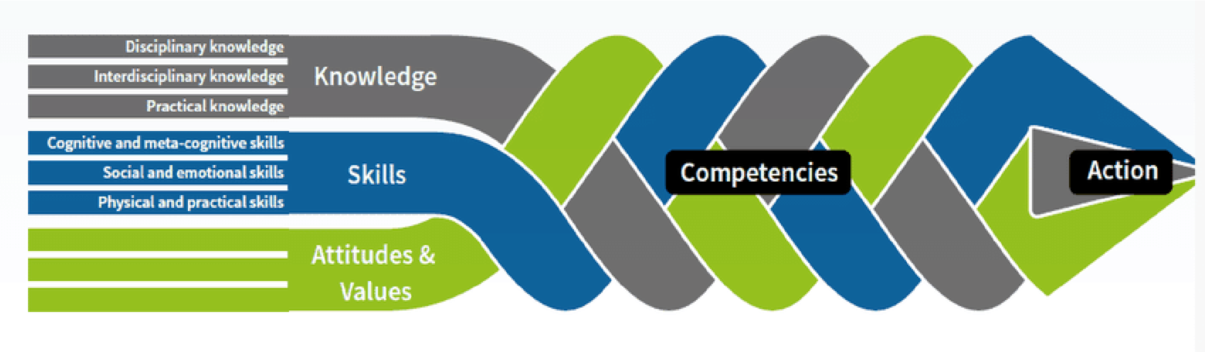

Figure 6: OECD 2030 framework for education

Core STEM competences, therefore, should be interwoven in the curriculum and developed by engaging in classroom practices informed by the seven characteristics of integrated STEM education, as identified by this review (c.f. Section 3). To recap, these seven characteristics of integrated STEM education include:

1. Core STEM Competences
2. Problem-Solving Design and Approaches
3. Disciplinary and Interdisciplinary Knowledge
4. Engineering Design and Processes
5. Appropriate Use and Application of Technology
6. Real-World Contexts
7. Appropriate Pedagogical Practices.

In summary, as illustrated in Table 14, our analysis of the range of STEM skills and competences referred to in literature identifies eight core STEM competences as central in integrated STEM education, namely (1) collaboration, (2) problem-solving, (3) innovation and creativity, (4) critical thinking, (5) disciplinary skills and competences, (6) self-regulation, (7) communication and (8) metacognitive skills.

Students need to develop these eight core STEM skills and competences in order to address complex and difficult everyday challenges/issues (Bailey et al., 2015). There is convincing evidence to demonstrate that STEM education strengthens student skills for transferring knowledge acquired between different contexts, as it focuses on real problems that students are familiar with (Sanders, 2009). This may also be attributable to the fact that the students understand more clearly why competences are important to learn through a programme that involves hands-on, project-oriented problem-solving techniques and appreciate the opportunities that STEM skills open for them (Bailey et al., 2015). Furthermore, it appears that STEM education contexts that focus on integrating all four STEM subjects improve student knowledge in the different STEM disciplines (National Academy of Sciences, 2014) and facilitates their connection.

However, recognition or development of engineering and technology competences are quite often neglected in STEM education (Kelley & Knowles, 2016). This apparent gap is surprising given that practical STEM skills have been recognised as a central competency for technological education along with the ability to use engineering skills, techniques, and tools in the field of technology (Barlex, 2007). Therefore, special attention should be paid to the development of the full range of core STEM competences across the STEM disciplines, especially those that heretofore have tended to receive less attention (i.e. engineering and technology). Otherwise, we will not be effectively preparing future generations to be STEM literate with "the ability to identify, apply, and integrate concepts from science, technology, engineering, and mathematics to understand complex problems and to innovate to solve them" (Balka, 2011, p. 7).

Having established the need for a common framework for integrated STEM education and identified the core STEM competences, the next section focuses on the integrated STEM curriculum and classroom practices.

Integrated STEM Curriculum

This section addresses Research Question 3 and aims to provide an overview of what an integrated STEM curriculum looks like and its links to the real world. The seven characteristics which were identified in Section 2 inform this section: Problem-Solving Design and Approaches, Core STEM Competences, Disciplinary and Interdisciplinary Knowledge, Engineering Design and Processes, Appropriate Use and Application of Technology, Real-World Contexts and Appropriate Pedagogical Practices. The section begins by exploring STEM education policy and curriculum. Then, knowledge and practices of integrated STEM education are discussed by utilising the characteristics of "Disciplinary and Interdisciplinary Knowledge", "Engineering Design and Processes" and "Appropriate Use and Application of Technology". The section concludes by outlining some examples for implementing integrated STEM education in classrooms, with particular reference to "Real-World Contexts" and "Appropriate Pedagogical Practices". See Appendix E which summarises practical classroom examples for STEM education.

It is broadly recognised in the literature that integrated STEM education allows students to develop a range of transversal skills, such as creativity and problem-solving skills; and it is highly important for STEM educators to develop such skills (Bailey et al., 2015). Additionally, the recent assessment and the guidelines for effective formative and summative assessments started to target technology-based assessments to measure "21st Century Skills". In practice, providing students with an integrated STEM education can help them to learn the connections to crosscutting concepts and real-world applications in a holistic manner (Kelley & Knowles, 2016). One of the lessons from the literature is that the process of integrating all STEM subjects in authentic contexts can be complex due to the lack of cohesive understanding of STEM education (Kelley & Knowles, 2016).

STEM Integration from Policy to Curriculum

The Committee on Integrated STEM Education (2014) sets out overall goals for an integrated STEM curriculum targeted to increase students' STEM literacy and 21st century competences, build a STEM-capable workforce and expand students' interest and engagement in STEM. In order to achieve these general goals, Hodges et al. (2016) articulate the following specific goals for students, teachers, universities, and for business (industry) stakeholders:

- Student goals focus on increasing career awareness, developing positive attitudes towards STEM, and strengthening conceptual understanding of STEM disciplines, including the ability to make connections among STEM disciplines (Margot & Kettler, 2019).
- Teacher goals involve content improvement, instructional strategies, improving attitudes toward STEM, and increased collaboration.
- Business goals involve informing the development of the product, understanding how schools work, and increasing collaboration.
- Finally, university goals seek to strengthen the relationship with schools, improve teaching and learning, and increase collaboration.

> **STEM literacy is creating the development of "STEM curricula" based on different skills and competences, such as problem-solving skills and practical skills including content knowledge and pedagogical knowledge, and these new curricula aim to elimate the gap between theory and practice.**
>
> *Martin-Paez et al. (2019)*

In addition to the importance of determining the goals of the integrated STEM curriculum, the decision of what approaches, theories, and competences to utilise for STEM integration is also significant.

STEM integration should be "intentional" and "specific" and both content and context should be considered in STEM integration *(English, 2017).*

Three forms of STEM integration emerge from the literature, as illustrated in Table 17. English (2017) identifies these three forms as (1) content integration including multiple STEM learning objectives in learning experiences; (2) integration of supporting content including the learning objectives of one main area (e.g., mathematics); and (3) context integration including the application of the learning objectives of one discipline in another. Similarly, Bryan et al. (2016) suggest three different paths for the integration of STEM content working with units or activities that: (1) simultaneously develop multiple learning objectives from the diverse STEM knowledge areas; (2) significantly cover content from some areas as support for developing the learning objectives involved in the main area to be worked on; and (3) start out from a specific context from an area of knowledge for locating learning objectives of others.

Table 17: Forms of STEM Education as identified by English (2017) and Bryan et al. (2016)

Forms of STEM Education (English, 2017)	Forms of STEM Education (Bryan et al., 2016)
(1) content integration including multiple STEM learning objectives in learning experiences	(1) simultaneously develop multiple learning objectives from the diverse STEM knowledge areas
(2) integration of supporting content including the learning objectives of one main area (e.g., mathematics)	(2) significantly cover content from some areas as support for developing the learning objectives involved in the main area to be worked on
(3) context integration including the application of the learning objectives of one discipline in another	(3) start out from a specific context from an area of knowledge for locating learning objectives of others.

Drawing on this literature the approach to STEM integration proposed by this report is that of 'content integration' which simultaneously develops multiple STEM learning objectives in learning experiences (Bryan et al., 2016; English, 2017). This approach requires that the contexts selected should "imply complex phenomena or situations via tasks that require students to use knowledge and skills from multiple disciplines, in a manner that context should be the backbone of STEM education" (Martin-Paez et. al., 2019, p.803).

Trying to implement such an approach to integrated STEM education is not without its issues and challenges. Some of which include:

1. Current STEM initiatives are not systematically connected to the curriculum (European Schoolnet, 2018).
2. Secondary education usually does not give flexibility to STEM subjects in the curriculum due to departmental agendas, requirements, content standards, and end-of-year examinations (Kelley & Knowles, 2016).
3. Some curriculum integration models are too general and lack rigor in domain-specific knowledge (Corlu et al., 2014).
4. STEM approaches may lead to a conflation of science and technology, or that the "T" and the "E" often tend to be downplayed in favour of the "S" and "M" (e.g. Hallstrom & Schonborn, 2019; Sanders, 2009).
5. Engineering is mostly neglected in STEM education research (Kelley & Knowles, 2016).
6. The link between the contexts covered and the different disciplines in the STEM interventions is lacking (68%, n = 13) in the majority of cases (Martin-Paez et al., 2019). As a result, it is common for there not to be an explicit connection between the different contents and the STEM disciplines in the descriptions of the educational interventions, in such a way that understanding how these are integrated can become difficult and even impossible (Martin-Paez et al., 2019).
7. Using a highly structured curriculum with rigid boundaries among STEM disciplines can weaken the effectiveness of the teachers (Corlu et al., 2014).
8. Some STEM teacher education curriculum ignores the teaching practice and pedagogical content knowledge in the program (Corlu & Corlu, 2010).
9. School level and type, age and experience of teachers at different school levels and types, and the budget can affect the STEM integration (Corlu et al., 2014).

The following recommendations can be considered to mitigate or overcome these challenges when moving towards adopting an integrated STEM curriculum. First of all, the impact of the initiatives/programs can be measured and according to the results, these initiatives/programs can be integrated into a structured national STEM curriculum (European Schoolnet, 2018). Next, an integrative approach to STEM education requires curriculum flexibility (Nistor et al., 2018), and a flexible curriculum can enable teachers to teach the STEM disciplines in their natural contexts (Corlu et al., 2014). Therefore, curriculum flexibility should be considered when developing STEM curricula. In a STEM curriculum, domain-specific knowledge should be provided while traditional boundaries of STEM disciplines are transcended without losing discipline integrity (Bybee, 2013; English, 2017).

While doing so, special attention should be paid to the integration of engineering as part of integrated STEM education as engineering is crucial and can act as a vehicle to teach and learn science and mathematics (Guzey & Moore, 2015). Engaging students in high-quality STEM education requires programs to include rigorous curriculum, instruction, and assessment, integrate technology and engineering into science and mathematics curriculum, as well as promoting scientific inquiry and the engineering design process (Kennedy & Odell, 2014). Finally, the literature demonstrates that teacher education is important when implementing STEM curricula. Therefore, developing teaching practices and pedagogical content knowledge of STEM teachers should be considered when preparing teacher education programmes.

Current STEM Education Practices in Europe

Nistor et al. (2018) published a seminal report highlighting the main STEM education practices in Europe. They surveyed 3,780 educators across 38 European countries. The report's key findings are divided into five main areas:

1. Pedagogical approaches used in STEM teaching: The study found that in general mathematics teachers adopted teacher-focused and less diverse and less contextualised pedagogies than the other, S-T-E-M subjects. However, there were some teachers adopting student-centred approaches with project/problem-based learning and collaborative learning.
2. Access to and use of resources and materials: Teachers pointed to insufficient access to experimental labs which might be a sign of insufficient opportunities to do practical work.
3. Professional development and support for STEM teachers: The majority of STEM teachers surveyed have not taken any ICT-related professional development or training related to innovative STEM teaching in the last two years.
4. Experience and educational level in STEM teaching: Teachers were willing to use constructivist approaches.
5. Teachers' attitudes and influence of the environment: The research found that three out of four of the surveyed teachers share a positive vision of innovative STEM teaching with their colleagues and head of school, and this is linked positively with the amount of innovation brought into the classroom. Teachers appear open to collaborating with STEM industries in various domains to enhance teaching and learning.

These findings suggest that resources (including use of digital tools and resources), innovative pedagogies and curriculum innovation, are particularly important in encouraging a more integrative approach to STEM teaching. They highlight the importance of using different pedagogical approaches in the classroom, such as formative assessment and collaborative learning. The authors found that more innovation was brought into classrooms where STEM teachers and their school administration are in synch over a positive vision about innovative STEM teaching. Based on the findings, Nistor et al. (2018) suggested that policymakers should (a) support innovative STEM teaching practices and networks based on Inquiry-Based Science Education (IBSE) and other student-centred pedagogies, (b) offer relevant professional development opportunities for STEM teachers and strengthening school-industry collaboration, (c) innovate the STEM education curriculum and assessment, (d) supporting the development and implementation of whole-school STEM-oriented strategies, and (e) strengthen trans-disciplinary collaboration to encourage the uptake of integrative STEM teaching.

However, if policymakers are to activate and operationalise the suggestions that Nistor et al. (2018) propose a systematic action plan needs to be developed which involves a wide range of stakeholders. The set of recommendations outlined by Honey et al. (2014, pp.8-10) if implemented would go a long way to ensuring that integrated STEM education initiatives would have some chance of surviving beyond the infamous "pilot" stage. These recommendations are wide-ranging and include the following:

Student-centred, inquiry-based, project/problem-based, collaborative (including but not limited to collaboration with STEM industries) and constructive teaching and learning approaches are endorsed for the integrated STEM curriculum (Margot & Kettler, 2019; Martin-Paez et al., 2019; Nistor et al., 2018). Furthermore, teachers' professional learning opportunities and access to and use of resources and materials should be considered when integrating STEM education into curriculum

(Nistor et al., 2018).

1. In future studies of integrated STEM education, researchers need to document the curriculum, program, or other intervention in greater detail, with particular attention to the nature of the integration and how it was supported. When reporting on outcomes, researchers should be **explicit** about the nature of the integration, the types of scaffolds and instructional designs used, and the type of evidence collected to demonstrate whether the goals of the intervention were achieved. **Specific** learning mechanisms should be articulated and supporting evidence provided for them.
2. Researchers, program designers, and practitioners who focus on integrated STEM education, and the professional organizations that represent them, need to develop a **common language** to describe their work.
3. Study outcomes should be identified from the outset based on **clearly articulated hypotheses** about the mechanisms by which integrated STEM education supports learning, thinking, interest, identity, and persistence. Measures should be selected or developed based on these outcomes.
4. Research on integrated STEM education that is focused on interest and identity should include more **longitudinal studies,** use multiple methods, including design experiments.
5. Designers of integrated STEM education initiatives need to be explicit about the goals they aim to achieve and design the integrated STEM experience purposefully to achieve these goals. They also need to better articulate their hypotheses about why and how a particular integrated STEM experience will lead to particular outcomes and how those outcomes should be measured.
6. Designers of integrated STEM education initiatives need to build in opportunities that **make STEM connections explicit to** students and educators (e.g., through appropriate scaffolding and sufficient opportunities to engage in activities that address connected ideas).
7. Designers of integrated STEM experiences need to attend to the learning goals and **learning progressions** in the individual STEM subjects so as not to inadvertently undermine student learning in those subjects.
8. Programs that prepare people to design and facilitate integrated STEM learning activities need to provide experiences that help these educators **identify and make connections among the disciplines explicit** to their students'. These educators will also need opportunities and support to **work collaboratively** with their colleagues, and in some cases, administrators and/or curriculum coordinators will need to play a role in creating these opportunities. Finally, some forms of professional development may need to be designed as partnerships among educators, STEM professionals, and researchers are developed.
9. Organizations with expertise in assessment research and development should create assessments **appropriate** for measuring the various learning and affective outcomes of integrated STEM education. This work should involve not only the modification of existing tools and techniques but also the **exploration of novel approaches.**
10. To allow for continuous and meaningful improvement, designers of integrated STEM education initiatives, those charged with implementing such efforts, and organizations that fund the interventions should explicitly ground their efforts in an **iterative model** of educational improvement.

Recurring ideas have been underlined and appear in bold in the text above to capture common ideas that permeate these recommendations. What is apparent is the need for clarity, making the connections between and across disciplinary knowledge and skills; learning objectives/learning progressions, etc. need to be specific and explicit, the development of a shared common language is paramount, coupled with appropriate measures for assessment with all stakeholders working collaboratively in an iterative way over time.

The next section aims to help determine appropriate practices for implementing integrated STEM education. The discussion will focus on three of the seven characteristics identified in section one, namely: "Disciplinary and Interdisciplinary Knowledge", "Engineering Design and Processes", and "Appropriate Use and Application of Technology".

Disciplinary and Interdisciplinary Knowledge

"Disciplinary and Interdisciplinary Knowledge" can be seen as the backbone of STEM disciplines (Martin-Paez et al., 2019) and the following points capture the complexities of these interrelationships:

- Science is both a body of knowledge that has been accumulated over time and a process—scientific inquiry—that generates new knowledge. Knowledge from science informs the engineering design process.
- Technology, while not a discipline in the strictest sense, comprises the entire system of people and organizations, knowledge, processes, and devices that go into creating and operating technological artefacts, as well as the artefacts themselves. Much of modern technology is a product of science and engineering, and technological tools are used in both fields.
- Engineering is both a body of knowledge—about the design and creation of human-made products—and a process for solving problems. Engineering utilizes concepts in science and mathematics as well as technological tools.
- As in science, knowledge in mathematics continues to grow, but unlike in science, knowledge in mathematics is not overturned, unless the foundational assumptions are transformed. Mathematics is used in science, engineering, and technology.

(adapted from Honey et al., 2014)

In contrast to traditional "segregated" STEM, integrated STEM requires the application of knowledge and practices from various STEM disciplines to solve complex and transdisciplinary problems (Struyf et al., 2019). Consequently, integrated STEM education approaches should require students to apply knowledge of mathematics, technology, science and engineering, design and carry out investigations, analyse and interpret data, and communicate and work with multidisciplinary teams (Martin-Paez et al., 2019; Ritz & Fan, 2015; Sanders, 2009). The integration of knowledge areas involves obtaining a final product greater than the sum of its individual parts. Designing integrated experiences providing intentional and explicit support for students is important in order to build knowledge and skill both within the disciplines and across disciplines. However, the literature is clear that students' knowledge in individual disciplines must be supported. Connecting ideas across disciplines is challenging when students have little or no understanding of the relevant ideas in the individual disciplines.

Students do not always or naturally use their disciplinary knowledge in integrated contexts and therefore they need support to elicit the relevant scientific or mathematical ideas in an engineering or technological design context. Students also need to connect those ideas productively, and to reorganize their own ideas in ways that come to reflect normative, scientific ideas and practices. These connected knowledge structures can support learners' ability to transfer understandings and competences to new or unfamiliar situations (Honey et al., 2014). However, developing disciplinary knowledge while also supporting students in making connections across disciplines is challenging. This concern is highlighted by Honey et al. (2014) by stating that curricula integrating mathematics or science with other STEM subjects are less likely to produce positive learning outcomes in mathematics than they are in science, although effect sizes can vary greatly depending on how science and mathematics are offered (sequentially, in parallel, together and separately, or together with either one subject as the dominant theme of the lesson or both subjects completely integrated).

> **The reason for including complex real-life examples is that "the cognitive priming is sufficient to first engage the student using cognitive tools that then create arousal of higher-level affect such as positive efficacy and interest". Creating and maintaining affect towards STEM through inquiry learning or problem-based learning can allow younger learners to generate their own understandings of the world through argumentation, presentation of evidence, and evaluation of evidence.**
>
> *Lamb et al. (2015)*

From a curriculum perspective, the STEM coordinator can help develop the complexity of ideas around the STEM curriculum. This can be achieved through cross-cutting approaches in each of the STEM disciplines developed in conjunction with a focus on challenging questions and working through authentic real-world problems requiring understanding and connections across not just STEM disciplines but other disciplines as well (Lamb et al., 2015). During STEM learning, knowledge is constructed. While some educational researchers argue that active knowledge construction can take place regardless of the teaching method or type of learning environment, others highlight the need to create constructivist learning environments that are typically student-centred (Struyf et al., 2019). During the knowledge construction process, the teachers' role is seen as a coach and facilitator rather than a dispenser of knowledge, as the focus is on problem-centred learning, inquiry-based learning, design-based learning, cooperative learning and other aspects, such as project-based and performance-based tasks (Mustafa et al., 2016; Thibaut et al., 2018a).

Bartholomew et al. (2019) support the use of design-based learning and believe that as students work with design portfolios, they may build upon previous knowledge, deepen their understanding of class material, and increase in self-reflection. Portfolios have also been linked with increases in technical skills, critical thinking, writing, and problem-solving (Nicolaidou, 2013). In addition to these practices, Eguchi and Uribe (2017) and Stohlmann et al. (2012) supported Daniels, Hyde and Zemelman's (2005) list of best practices for teaching mathematics and science to guide integrated STEM educators:

- using manipulatives and hands-on learning
- cooperative learning
- discussion and inquiry
- questioning and conjectures
- using the justification of thinking
- writing for reflection and problem solving
- using a problem-solving approach
- integrating technology
- teacher as a facilitator
- use assessment as a part of instruction.

Engineering Design and Processes

Engineering design and practices are generally neglected in the literature and therefore, need to be promoted more (Guzey & Moore, 2015; Kalaian et al., 2018; Kelley & Knowles, 2016; Mohd Shahali et al., 2017; Shahbazi et al., 2016). Kelley and Knowles (2016) advocate that using engineering design as a catalyst to STEM learning and overcoming the limited view of technology is highly significant to bringing all four STEM disciplines on an equal platform for teaching STEM in an integrated approach. STEM content and practices should be taught and experienced together, and by doing so, "an integrated STEM approach can provide a platform through a community of practice to learn the similarities and differences of engineering and science" (Kelley & Knowles, 2016, p. 7). Similarly, according to Guzey and Moore (2015), at the K-12 level, engineering education should (1) include and emphasize engineering design, (2) incorporate important and developmentally appropriate science, mathematics, and technology knowledge and skills, or (3) promote engineering habits of mind which are the general principles of K-12 engineering education. To help implement the engineering design process into integrated STEM classes, the model that Lesseig et al. (2017) presented can be utilised (See Figure 7).

> **The integrated STEM education research referring to engineering and technology is very limited. Using engineering design as a catalyst to STEM learning and overcoming the limited view of technology are highly significant to bring all four STEM disciplines on an equal platform for teaching STEM in an integrated approach**
>
> *(Kelley & Knowles, 2016).*

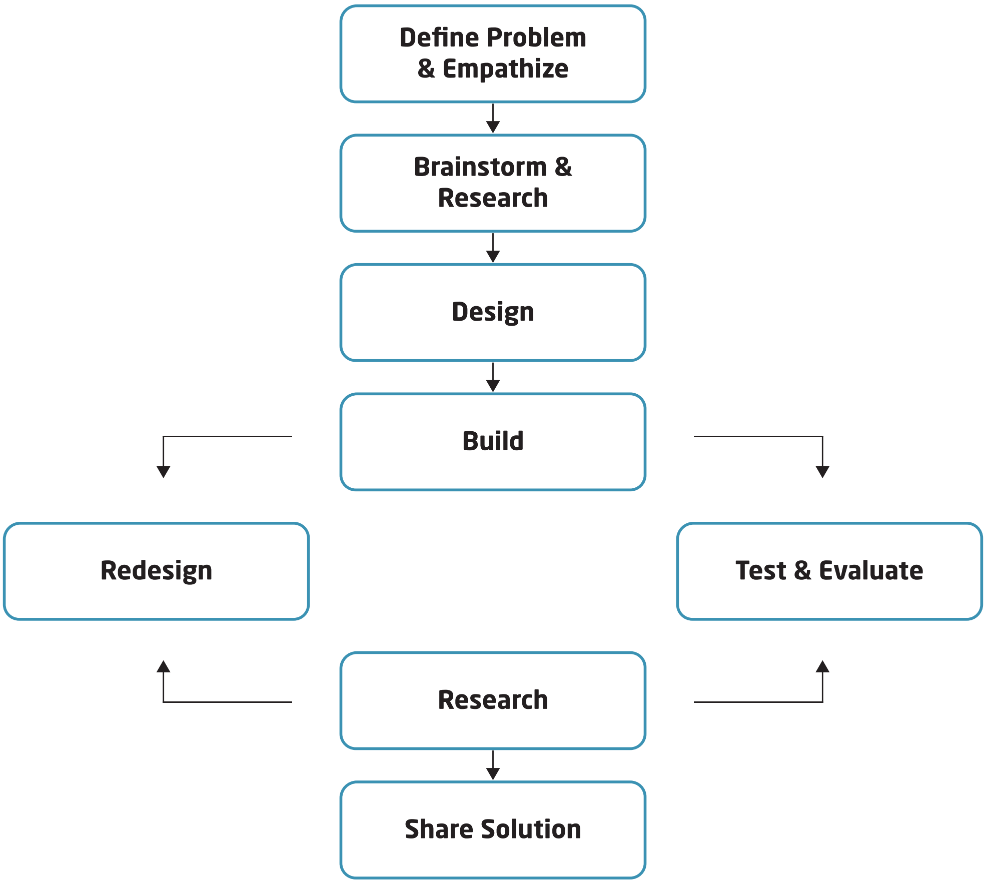

Figure 7: Engineering design process used in Teachers Exploring STEM Integration (TESI) Project (Lesseig, K., Slavit, D. & Holmlund Nelson, T., 2017, p.18)

It should be noted that Shahbazi et al. (2016) and Kalaian et al. (2018) also provide a useful example of integration of engineering into STEM.

Appropriate Use and Application of Technology

"Appropriate Use and Application of Technology" is highlighted as an important characteristic when integrating STEM disciplines (Eguchi & Uribe, 2017; Lesseig et al., 2017; Shaughnessy, 2013; Stohlmann et al., 2012). While Lesseig et al. (2017) and Shaughnessy (2013) were focusing on the use of appropriate technology, Johnson (2013) found technology design important when integrating STEM disciplines. Another perspective provided by Moore et al. (2016), Radloff and Guzey (2016), and Aydin-Gunbatar et al. (2018) view engineering design as part of developing relevant technologies. This suggests that during the STEM integration process, technology can either be viewed as a tool to facilitate teaching or a product or service produced as part of classroom practices. However, Nistor et al. (2018) found that technical support for teachers and students was insufficient. Some examples of technology use in the classroom practices include the use of simulations (Nistor et al., 2018) and 3D technologies (Ibáñez & Delgado-Kloos 2018), developing robots (Blackley & Howell, 2019), virtual reality (O'Leary et al., 2018) and programming (Guzdial & Morrison, 2016).

During the STEM integration process, technology can either be viewed as a tool to facilitate teaching or a product or service produced as part of classroom practices.

What must be acknowledged is that there is a wide range of perceived barriers and challenges that seem to be impacting the implementation of an integrated STEM approach which include: (1) pressure to prepare students for exams and tests (77%), (2) insufficient technical support for teachers (73%), (3) school space organisation (classroom size and furniture, etc.) (69%), (4) budget constraints in accessing adequate content/material for teaching (68%), and (5) lack of pedagogical models on how to teach STEM in an attractive way (67%) (Nistor et al., 2018, p.39).

Besides, finding a context to help educators understand how the four STEM disciplines work together in an interconnected way with a strong connection to life, is essential (Corlu et al., 2014), The general pattern is that science and mathematics are prominent with engineering and technology mostly neglected (Kelley & Knowles, 2016). A possible solution to this imbalance is to utilise technology and engineering to develop representations of the real-world since technology and engineering involve real-life applications. Robotics, engineering design and construction activities are commonly used activities in integrated STEM education. Some "real-world" examples to transform these theoretical discussions into classroom practices are outlined in the next section.

When developing STEM practices, main factors affecting STEM education should be taken into account, which are (1) pressure to prepare students for exams and tests, (2) insufficient technical support for teachers, (3) school space organisation, (4) budget constraints in accessing adequate content/ material for teaching, and (5) lack of pedagogical models on how to teach STEM in an attractive way.

(Nistor et al., 2018).

'Real-World' Examples for Implementing Integrated STEM Education in Classrooms

Two of the seven characteristics of integrated STEM education, "Real World Contexts" and "Pedagogical Practices", inform the examples highlighted in this section.

Integrative learning and curriculum integration theories refer to connecting the subject matter to real-life to make it more meaningful to students through curriculum integration (Beane, 1997). It makes sense that instead of being taught in a vacuum, math and science should be brought to life through students' need to be used to solve a real problem (Margot & Kettler, 2019). Many studies refer to the importance of making this connection with real-world problems (e.g., Blackley & Howell, 2019; Bybee, 2013; Kelley & Knowles, 2016; Mohd Shahali et al., 2019; Moore et al., 2016; Stohlmann et al., 2012), that help make student learning more meaningful (Blackley & Howell, 2019; Türk et al., 2018).

Making connections in STEM education to "real-world problems" is important

(EL-Deghaidy et al., 2017)

Radloff and Guzey (2016) present five characteristics including the use of real-world problems in order to distinguish integrated STEM instruction from other teacher pedagogy: (1) the content and practices of one or more anchor science and mathematics disciplines define some of the primary learning goals; (2) the integrator is the engineering practices and engineering design of technologies as the context; (3) the engineering design or engineering practices related to relevant technologies requires the use of scientific and mathematical concepts through design justification; (4) the development of 21st century skills is emphasised; and (5) the context of instruction requires solving a real-world problem or task through teamwork. The use of engineering design processes and finding a solution to real-world problems are key characteristics that can be utilised when developing integrated STEM activities that are highlighted in the literature (e.g., Aydin-Gunbatar et al., 2018).

Some real-life examples and tools that can be used when developing an integrated STEM curriculum are outlined in Appendix F.

Five characteristics to distinguish integrated STEM:

1. **the content and practices of one or more anchor science and mathematics disciplines define some of the primary learning goals**
2. **the integrator is the engineering practices and engineering design of technologies as the context**
3. **the engineering design or engineering practices related to relevant technologies requires the use of scientific and mathematical concepts through design justification**
4. **the development of 21st century skills is emphasized**
5. **the context of instruction requires solving a real-world problem or task through teamwork.**

Radloff and Guzey (2016)

Appropriate Pedagogical Practices

A range of pedagogical practices and classroom practices were advocated in the literature related to STEM programs that were developed. For example, the SEEA group in Scotland and the Australian Government, and American Society for Engineering Education highlight the significance of developing specialized STEM programs with **inquiry teaching methods** at all educational stages. Based on this approach, they developed a **project-based integrated STEM curriculum** in Secondary Education (Pitt, 2009; Ritz & Fan, 2015) in which students' learning process contained three phases for each project lasting for about 1 hour.

1. The first phase involved a 5 minute-teacher-oriented activity with problem-based learning method. The teacher provided several questions on a special STEM theme with a real-life context. Students were encouraged to ponder over the strategies of the experimental design and alternative solutions to the problems that they may encounter when they focus on a special STEM theme.
2. The second phase involved a 40-minute student-oriented section, in which students had their own creative ideas and designed their personal projects. Students were paired and each pair shared their ideas with each other and made a decision to choose a better experimental design. Students were encouraged to apply scientific and mathematics knowledge to their experimental designs. They constructed their designs and explored new ideas. They redesigned their experiments when necessary. Students drew a conclusion from experimental results and explained the experimental phenomenon with the integrative knowledge of science and mathematics.
3. The third phase was about 15 minutes. Each pair presented the experimental phenomena and results of their projects and tried to address the key concept and principles of the scientific and mathematics knowledge related to the STEM theme. In this phase, the role of the teacher was to evaluate students' statements and give supplementary explanations.

The authors (Pitt, 2009; Ritz & Fan, 2015) also provide projects for first to sixth-grade students. For example, first-grade project called "purple floor" was designed to learn about the colour change by reaction with iodine (See further examples in Appendix F).

Design features of the Augmented Reality (AR) activities allow students to acquire basic competencies related to STEM disiplines, and future applications need to include metacognitive scaffolding and experimental support for inquiry-based learning activities.

Ibanez and Delgado-Kloos (2018)

English (2017) provided some suggestions to advance elementary and middle school STEM education. Similar to Martin-Paez et al. (2019), English (2017) supported the three forms of STEM integration proposed by Bryan et al. (2016). English (2017) however, argued to what extent students' learning of the STEM disciplines should be governed by integrated activities and discussed if total integration would do justice to students' learning of core disciplinary content and processes. English (2017, p, S9) believes that "an integrated STEM activity is ideal for consolidating and extending units of disciplinary study, such as concepts of light in science and measurement processes in mathematics forming the basis for applying STEM ideas in building an optical instrument". English (2017) provided a STEM integration matrix to analyse and categorise the integrated activities that might be incorporated within a school curriculum and dedicated a section about designing Integrated STEM-Based Experiences. A pedagogical approach was the use of **STEM-based modelling activities** as English (2017) believes that through giving consideration to the links between modelling and engineering design processes, the foregoing pedagogical affordances could be enacted within STEM-based activities through real-life examples. English also sees STEM-based modelling as a cyclic, generative learning activity that involves modelling and engineering to facilitate the solving of authentic problems involving STEM content, processes, and contexts.

Integrated STEM education "is a space for students to apply their discipline knowledge to **create products and/or solve problems that can be made or solved using engineering principles"** (Blackley & Howell, 2019). Students should be exposed to real-life situations that demonstrate how STEM knowledge and skills and 21st-century competences can be applied in different contexts.

One example tool to build capacity in classroom teachers and engage students was given as WeDo which spotlights 21st century competences in classroom practice. Blackley and Howell (2019) provided an example of the four STEM disciplines through robotics. They suggested WeDo 2.0, LEGO Mindstorms ® EV3 robots to provide rich opportunities for integrated STEM education, high-level programming, complex component assembly, and the development of 21st century competences. They also used Edison robots which is an engaging tool for teaching hands-on computational thinking and computer programming. Edison robots work with any compatible LEGO brick building system and could value-add WeDo kits or basic LEGO kits. Kim et al. (2015) also believe that robotics can be effective for STEM education due to (1) enabling real-world applications of the concepts of engineering and technology, (2) helping to remove the abstractness of science and mathematics, (3) enhancing students' mathematics and science performance, (4) improving students' engineering design skills, (5) enhancing students' STEM knowledge, and (6) student-centred teaching.

Margot and Kettler (2019) recommend that schools should refine their **instructional pedagogy** through an interdisciplinary approach to reveal students' STEM potential (Margot & Kettler, 2019). This approach allows students to make real-world connections and prepare for STEM pathways and careers. The authors advocate engineering and technology should be integrated into traditional math and science classrooms, and **teaching through the engineering design process** would be one approach to achieve this. Margot and Kettler (2019) give some suggestions to help this integration, such as:

- using hands-on, practical applications of content to solve students' challenges,
- introducing students to STEM professions,
- using a project-based approach,
- help students apply content knowledge to solve problems,
- utilising the engineering design process in the classroom to make real-connection to the world.

Kennedy and Odell (2014) advocate general strategies that teachers can put into practice in their classrooms to support quality integrated STEM education programs and curricula:

- Include rigorous mathematics and science curriculum and instruction;
- At a minimum, (if separate STEM courses are not available in all areas) integrate technology and engineering into the science and mathematics curriculum;
- Promote engineering design and problem-solving—(scientific/engineering) the process of identifying a problem, solution innovation, prototype, evaluation, redesign—as a way to develop a practical understanding of the designed world;
- Promote inquiry—the process of asking questions and conducting investigations—as a way to develop a deep understanding of nature and the designed world (NSTA 2004);
- Be developed with grade-appropriate materials and encompass hands-on, minds-on, and collaborative approaches to learning;
- Address student outcomes and reflect the most current information and understandings in STEM fields;
- Provide opportunities to connect STEM educators and their students with the broader STEM community and workforce;
- Provide students with interdisciplinary, multicultural, and multi-perspective viewpoints to demonstrate how STEM transcends national boundaries providing students a global perspective;
- Use appropriate technologies, such as modelling, simulation, and distance learning to enhance STEM education learning experiences and investigations;
- Be presented through both formal and informal learning experiences;
- Present a balance of STEM by offering a relevant context for learning and integrating STEM core content knowledge through strategies such as project-based learning.

For an effective STEM instruction, EL-Deghaidy et al. (2017) indicate the importance of (1) the recognition that real-life problems, (2) developing a coherent set of standards and curriculum, (3) creating teachers with high capacity, (3) improving a supportive system of assessment and accountability, (4) providing adequate instructional time, and (5) giving equal opportunity to access quality STEM activities.

Authentic learning is an essential component of STEM education and STEM literacy. Hallstrom and Schonborn (2019) attempt to synthesise key publications that document relationships between authenticity, models and modelling, and STEM education to foster integrated and authentic STEM education. The implications drawn from the synthesis presented in this commentary for STEM education are as follows:

The importance of the following approaches and perspectives is commonly mentioned in the literature:

1. **Authenticity**
2. **Models and modelling**
3. **Identifying real-world problems**
4. **Active learning**

(e.g., Davies & Gilbert, 2003; Freeman et al., 2014; Gilbert et al., 2011; Hallström & Schönborn, 2019; Niss, 2012; Roth, 2012; Williams, 2011).

- Authenticity must be viewed as a cornerstone of STEM literacy (Roth, 2012).
- Models and modelling processes can bridge the gap between STEM disciplines through authentic practices (France, 2017; Gilbert, 2004)
- Models and modelling should be used as a means to promote STEM literacy and the transfer of knowledge and skills between contexts, both in and out of the STEM disciplines (Niss, 2012).
- Modelling activities can serve as a meaningful route toward authentic STEM education (Davies & Gilbert, 2003; Gilbert, 2004).
- Teaching authentic modelling processes must be rooted in explicit and tested frameworks that are based on the practice of the STEM disciplines (Justi & Gilbert, 2002), such as the approach provided by Nia and de Vries (2017).

- Authentic STEM education should be driven by developing interaction between STEM subjects in parallel with maintaining the integrity of each subject (Williams, 2011).
- Integrating science, technology, engineering, and mathematics remains a complex challenge that calls for “a new generation of STEM experts” (Kelley & Knowles, 2016).
- Authentic STEM education should focus on decreasing the vocational—and often politicised—notion of STEM as a way to increase economic competitiveness in favour of promoting STEM as an interdisciplinary way of learning authentic science, technology, engineering, and mathematics (Pitt, 2009; Williams, 2011).

Furthermore, Hallström and Schönborn (2019) refer to the relevance of STEM literacy to goals of national economic growth and the development of the individual student in terms of acquiring knowledge, attitudes, and skills to identify the real-world problems through the integrated STEM disciplines. However, the authors support incorporating two or more of the STEM disciplines on equal terms, which considers the central epistemological concerns of each discipline as well as the rich historical heritage and common concepts and practices.

To conclude, disciplinary and interdisciplinary knowledge, engineering design process and practices, as well as the use of appropriate technology, informed the design of the learning activities in the reviewed research. In addition, the use of modelling and real-world problems, developing authentic activities, and engaging students in active learning environments were highlighted as being important pedagogical practices. Some example activities were provided throughout the section, which can be drawn upon when developing learning activities.

STEM Education in Teacher Education

This section relates to Research Question 4 and aims to present teachers' beliefs towards integrated STEM education, the challenges in developing teacher understanding of STEM education and how teachers can be supported as they build their understandings around learning design for integrated STEM education.

It is important to acknowledge that teacher education does not take place in a vacuum, there are many factors that influence how it is shaped and how particular developments can be driven by policy and curriculum needs and demands at the school and classroom level. Increasingly, it is becoming apparent that there needs to be a high level of policy coordination between K-12 and higher education in order to increase the quality of pre-service teacher education (Corlu et al., 2014). In addition, STEM education policies should formulate a concept and procedural connections for the purpose of developing instructional material and implementing teaching practices (Kurup et al., 2019). These connections could perhaps be made clearer for all stakeholders by making use of the four-dimensional framework of purpose, policy, program, and practices formulated for STEM education by Bybee (2013). However, the issues and challenges in the current school structures remain, and therefore there is a need to educate teachers about the changes that need to take place within schools.

Issues and Challenges of Teachers When Applying Integrated STEM Education

It is clear from the literature that teachers experience several issues and challenges when implementing integrated STEM education in their classroom (e.g., Lesseig et al., 2017; Margot & Kettler, 2019; Park et al., 2017), which might affect the efficacy of STEM teaching and learning. Better understanding the challenges that teachers face is likely to help facilitate the implementation and success of STEM programs. Both school administrators and teacher educators need to determine what supports teachers feel would improve their ability to prepare students for STEM education and careers (Margot & Kettler, 2019). Thus, there is a need to increase teachers' awareness towards potential challenges that they can experience and educate teachers about the changes that should take place within schools to overcome these potential issues/barriers. This section aims to inform teacher education programs to provide professional learning experiences in STEM education by illustrating the issues and challenges of implementing integrated STEM education.

During the STEM integration process, teachers are viewed in the literature as important facilitators to engage students in meaningful authentic learning experiences that enrich their deep content understanding in the STEM disciplines, help students establish connections to everyday life experiences, and help students to develop 21st century skills, such as outlined in section 3.2. Even though implementing STEM-based curricula is feasible in middle school, the interdisciplinary and open-ended nature of STEM projects can make this implementation difficult (Lesseig et al., 2017) which results in many challenges throughout the integration of STEM education. Sometimes, even though teachers are provided with resources and tools, they still experience issues and challenges. These issues and challenges are listed in Appendix G. Common issues and challenges are extrapolated and categorised in Table 18.

Table 18: Issues, challenges and factors perceived by teachers that have an impact on the enactment of STEM education practices

Type of the Challenge	Details	Authors
Pedagogical challenges	• Teachers and students having a different ways of learning	• Lesseig, Slavit, & Nelson (2017)
	• Lack of information on what are appropriate pedagogical practices in STEM education	• Adams et al. (2014); Bers (2008); Kim et al. (2015); EL-Deghaidy et al. (2017); Park et al. (2017)
	• Applying STEM pedagogy requiring some fundamental shifts in how classroom environments are established (including pedagogy, curriculum, assessment, support and training)	• Margot & Kettler (2019)
	• Teachers are not confident in using of new technologies, e.g. educational robotics	• Pittí, Curto, Moreno, & Rodríguez (2013)
	• Teachers' beliefs, understanding, capacity and skills	• EL-Deghaidy et al. (2017)
	• Lack of quality assessment tools	• Margot & Kettler (2019)
	• Student awareness of what STEM is and what are STEM disciplines	• EL-Deghaidy et al. (2017); Margot & Kettler (2019)
Structural challenges	• Separate content courses	• Lesseig, Slavit, & Nelson (2017)
	• Students have separate mathematics and science teachers	• Lesseig, Slavit, & Nelson (2017)
	• Typical school structures, e.g. rigid bell schedules, class capacity	• Margot & Kettler (2019); Lesseig, Slavit, & Nelson (2017); EL-Deghaidy et al. (2017)
Curricular challenges	• Tension between needing to meet grade-level content standards for mathematics and science while maintaining the exploratory, real-world components of STEM challenges	• Lesseig, Slavit, & Nelson (2017)
	• Engineering is a missing discipline in STEM teacher education	• Adams et al. (2014); Kim et al. (2015)
	• The integrated nature of STEM curriculum (particularly at the high school level)	• Margot & Kettler (2019)
	• Curriculum content	• EL-Deghaidy et al. (2017)
	• Time issues e.g. Planning time and Lack of time to teach STEM	• EL-Deghaidy et al. (2017); Margot & Kettler (2019); Park et al. (2017)
Teacher challenges	• Lack of resources/facilities., e.g. teachers lack resources needed to effectively implement inquiry-based STEM learning experiences in classrooms, lack of instructional resources	• EL-Deghaidy et al. (2017); Margot & Kettler (2019); Johnson (2006); Park et al. (2017)
	• Lack of administrative support	• EL-Deghaidy et al. (2017); Park et al. (2017)
	• Reluctance of teachers to collaborate	• EL-Deghaidy et al. (2017); Park et al. (2017)
	• Lack of teacher support from other disciplines (e.g. mathematics, technology) and from the school management	• Margot & Kettler (2019); EL-Deghaidy et al. (2017)
	• Lack of professional development, lack of teachers' preparedness	• EL-Deghaidy et al. (2017); Margot & Kettler (2019); Park et al. (2017)
External challenges	• Parents, e.g. Lack of parental participation) and parent awareness of what STEM is	• Park et al. (2017); EL-Deghaidy et al. (2017)
	• There is a lack of information and systematic evaluation of teacher education on robotics for teaching	• Arlegui, Pina, & Moro (2013); Osborne, Thomas, & Forbes (2010)

In Table 18, five types of issues and challenges were identified in the integrated STEM literature. These challenges are:

1. Pedagogical challenges
2. Structural challenges
3. Curricular challenges
4. Teacher challenges
5. External challenges

To overcome these issues and challenges and facilitate student learning and development, teachers need to be engaged in professional learning experiences, work together with teachers from other disciplines to identify crosscutting content or skills to help teachers clear up their misunderstandings about other disciplines, and become familiar with current practices of an interdisciplinary curriculum including parallel, cross-disciplinary and infusion models. Enabling teachers to move from traditional to innovative STEM education, means that teachers should be supported to develop deep interdisciplinary content knowledge, a strong belief in innovative teaching strategies, and the development of strong teacher teams that are able to create a culture of learning in schools through professional communities. Collaborative and supportive professional STEM communities can be created in an effective STEM school culture. In this STEM school culture, the exchange of experience and constant dialogue between teachers and administrators is highly emphasised (EL-Deghaidy et al., 2017). The involvement of administrators in the integration process can facilitate the collaboration between teachers, administrators, and students to overcome the challenges to implementation and create and enact STEM curricula in line with the kinds of learning experiences today's students need and desire (Lesseig et al., 2017). The role of partnership with universities and industries should not be neglected in these STEM communities. Teachers believe that partnerships with industries and universities are locally and regionally useful for developing students' interest in STEM disciplines and careers through direct interaction with the STEM community in their daily life (EL-Deghaidy et al., 2017).

In short, we recommend these common challenges that teachers face anchor and form the basis of effective teacher education programmes. There needs to be a planned and coherent approach to the development of teacher professional learning programmes to ensure that there is a fully integrated approach to STEM education, where 'engineering' is not being left out of a STEM pedagogical model (Johnson & Cotterman, 2013). Before putting STEM in action, teachers' perceptions and expectations should be considered as well as the challenges to conceptualise the instructional practices of STEM incorporating all four disciplines (EL-Deghaidy et al., 2017).

Teachers' Beliefs About Integrated STEM Education

When we begin to understand the perceptions of teachers, we can come up with a collective and instructional representation of STEM education for STEM teachers to learn about STEM education easily (Radloff & Guzey, 2016). Therefore, the perception and beliefs of teachers in STEM education are of importance because these beliefs and values influence teachers' pedagogical orientation.

Understanding the centrality of teachers' beliefs is critical, and cannot be underestimated, as it impacts on (a) their instructional decision-making and practices (Nathan et al., 2010), (b) their interpretation and actual classroom practices regarding what they have learned from training and professional development (Hughes, 2005), and (c) their efforts and resistance level toward new practices and reforms (Richardson, 2003).

The essential point is that teachers' efficacy beliefs and the value they place on STEM education influence their willingness to engage and implement STEM curriculum (Margot & Kettler, 2019). Margot and Kettler (2019) examined teachers' perceptions of utilising STEM pedagogy and found that age, gender, and STEM experiences of teachers may play a role in their perceptions of STEM education (e.g. their support and enthusiasm). This finding might relate to the point mentioned in the challenges about teachers' beliefs, understanding, capacity, and skills (EL-Deghaidy et al., 2017). Margot and Kettler's (2019) study found that teachers felt that support in some areas, such as collaboration with peers, quality curriculum, STEM pedagogy best practices, district support, prior experiences, and effective professional development would improve their effort to implement STEM education.

> **The professional learning (professional development) should provide a strong conceptual framework of an integrated STEM approach and build teachers' confidence in teaching through an integrated STEM approach.**
>
> *Kelley and Knowles (2016)*

Teachers' perceptions of STEM also influence the way that they develop their understanding of STEM, and therefore the way they teach STEM. The teachers' perception of STEM, their personal knowledge, and understanding of that knowledge, is intrinsically linked to the effectiveness of STEM implementation in their own classroom practice (Bell, 2016). Bell (2016) reports the ways Design and Technology (D&T) teachers perceive STEM, and how the variation of perception relates to D&T pedagogy, as summarised in Table 19.

Table 19: Categories of description (adapted from Bell, 2016)

Category	Description
STEM knowledge learned from external relationship	STEM as an externally imposed concept, where there is an awareness knowledge is limited and emotionally evokes feelings of apathy, fear, and apprehension
STEM knowledge learned from internal relationship	STEM as surface knowledge, deficit in understanding, but demonstrating an internally imposed desire to acquire new learning
STEM understanding learned from internal relationship	STEM as personal development, evidence of a growing confidence to confront their own understanding and to acquire and apply new knowledge
STEM understanding taught through internal relationship	Pragmatic approach to the delivery of STEM, displays complete understanding

Bell (2016) also showed that the differences between science and D&T teachers' perceptions of each other's subject created tension and affected the design and implementation of STEM learning experiences, which could also end up in a failure to develop cross-curricular activities. It is also the case that many STEM educators feel uncomfortable with using STEM instruction and content (Radloff & Guzey, 2016), and consequently, are not willing to adopt STEM approaches in their classrooms (Nadelson & Seifert, 2013). This may in part be due to the complexities of what is understood by STEM. These complexities are captured by Radloff and Guzey's (2016) work with pre-service teachers.

Teachers merely have basic conceptions of STEM, which could disrupt the implementation of STEM teaching approaches and the development of students' STEM understanding (Radloff & Guzey, 2016). Radloff and Guzey (2016) examined pre-service teachers' conceptualisation of STEM and determined six main types of STEM visualizations (See Figure 8). In Figure 8, these visualizations are referred by letter markers (a-f) as (a) Nested, (b) Transdisciplinary, (c) Interconnected, (d) Sequential, (e) Overlapping, and (f) Siloed. These visualisations help to illustrate the complexities of what is understood by STEM.

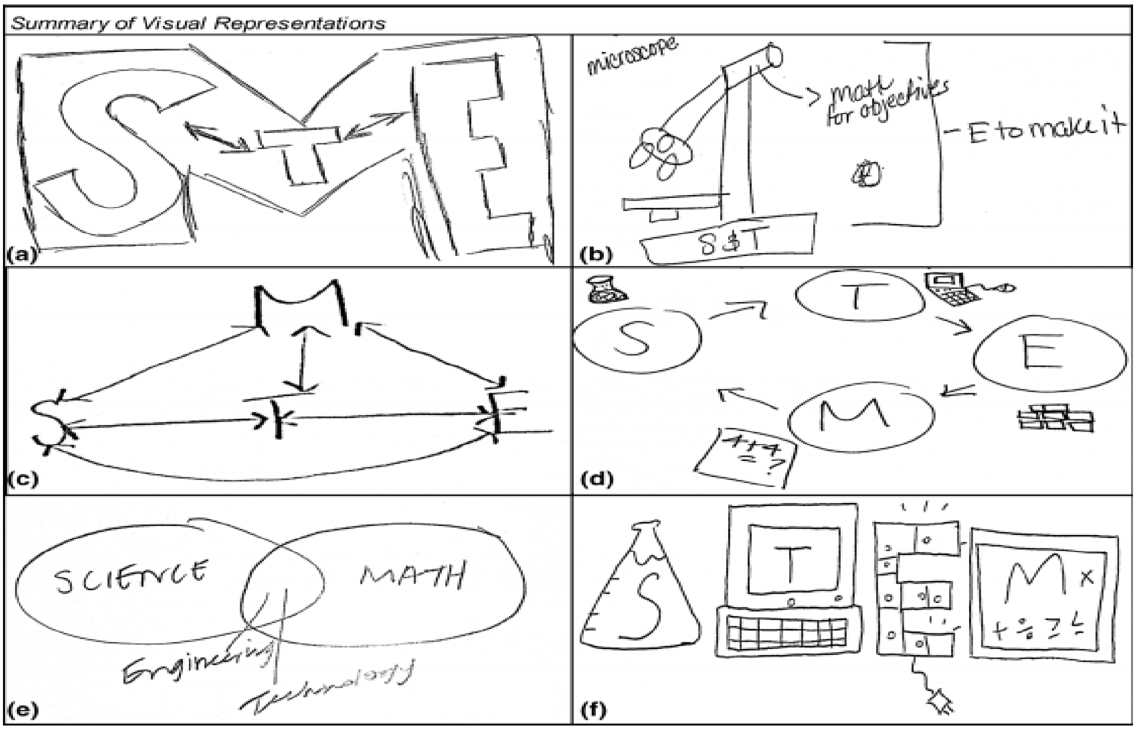

Figure 8: Summary of visual representations (Radloff & Guzey, 2016)

The most common rationale for participant visualizations was that "STEM disciplines are related". Pre-service teachers defined STEM education within four themes, namely, (a) Instruction, (b) Discipline, (c) Exclusion, and (d) Integration. The majority of participants defined STEM from an instructional perspective, which included real-world application and context, creative and critical thinking, discovery or hands-on learning, problem-based learning (PBL), student-centred instruction, and working in teams. After defining STEM education, participants were asked about the connection between the STEM disciplines, and the majority of participants chose a connectedness of "6" or greater (e.g., moderate connection or greater). All visualisations represented interconnectivity.

These findings illustrate that coupled with effective pedagogical instruction, STEM visualizations may help provide effective visual frameworks for all STEM educators by which to better internalize STEM knowledge.

In addition, it must be acknowledged that the beliefs, understandings, and intentions of pre-service primary teachers to teach STEM is highly important, as although pre-service teachers may not have a strong understanding, they have strong beliefs and intentions to teach STEM in their future career (Kurup et al., 2019). Kurup et al.'s (2019) study pointed at a gap between beliefs, understandings, and intentions to teach with capacity and confidence, and a need for innovative practices in teacher preparation and teacher professional development to bridge the gap. The results of this study inform how to teach STEM in primary schools and what teachers need for the future teaching of STEM.

There is a perceived need for professional development in STEM facilitating teachers' integration of STEM disciplines, providing them with an understanding of pedagogical approaches, and showing teachers the connection of STEM to real-life with the twenty-first century competences.

Kurup et al. (2019)

To conclude, it can be inferred from these findings that for students to become STEM literate, STEM teachers should be supported to explore the ways in which they can best foster mutually reciprocal arrangements with their STEM counterparts leading to the creation of an interdependent, cooperative and symbiotic curriculum. Teachers working as 'STEM Thinkers' will begin to appreciate how STEM disciplines interconnect and it is hoped will realise the impact of integrated STEM education for society (Reeve, 2015).

Practices Utilised to Design Appropriate Teacher Professional Learning

There is a pressing need to invest in professional learning for practising (in-service) teachers (Corlu et al., 2014) to support them in becoming confident, competent, and skilled teachers who can design integrated STEM learning experiences for their students. However, as shown in the above discussion what is equally important is a focus on developing preservice teacher education programmes. In an integrated teacher education program, pre-service teachers can be educated to become the driving force and genuine supporters of the reforms that aim to transition from the departmentalised model of STEM teaching and learning to an integrated model that promotes innovation (Furner & Kumar, 2007). Kurup et al. (2019) suggest some future practices in teacher preparation to build confident, competent, and skilled teachers in STEM, which can contribute to creating a 21st-century skilled workforce in STEM-related fields. These include:

- Providing experiences in STEM for future teachers so that they can apply knowledge and skills in actual practices.
- Developing the ability to integrate knowledge and understanding of disciplines to STEM-related experiences.
- Integrated knowledge should have sound pedagogical practices and coherence in the curriculum to implement best practices connected to daily life in STEM-related issues.
- Ongoing professional development in STEM for all teachers.
- Linking school and out-of-school experiences to STEM-related activities.

Future practices should involve:

- **Providing experiences in STEM for future teachers so that they can apply knowledge and skills in actual practices**
- **Developing ability to integrate knowledge and understanding of disciplines to STEM-related experiences**
- **Integrated knowledge and pedagogical practices connected to daily life in STEM-related issues**
- **Linking school and out-of-school experiences to STEM-related activities.**

Kurup et al. (2019)

By adopting integrated teacher education programs, future teachers are more likely to be prepared with the knowledge, skills, and beliefs to effectively design and implement STEM education that increases the innovation capacities of students (Cuadra & Moreno, 2005).

However, there are issues that practising teachers are faced with when integrating and developing STEM practices that also need to be addressed. For example, many STEM teachers have not participated in any ICT-related professional development related to innovative STEM teaching recently (Nistor et al., 2018), There are concerns about the need for resources for personalised learning and special needs learners, as well as teachers' use of traditional instruction more than IBSE. Nistor et al. (2018) indicate that teachers tend to update their knowledge online and in their own time, rely on peer support to improve their STEM teaching. and are open to collaborating with STEM industries in various domains to enhance teaching and learning. The need to provide a range of professional experiences and supports for STEM teachers is evident.

Importantly, professional learning should provide a strong conceptual framework of an integrated STEM approach and build teachers' confidence in teaching through an integrated STEM approach. This would include a focus on key learning theories, pedagogical approaches, and building awareness of research results of current STEM educational initiatives (Kelley & Knowles, 2016).

European Schoolnet (2018) advocates that the aim of providing professional learning to STEM educators should be to get the teachers into demanding projects with their students and support them to develop their pedagogical STEM skills on the job. To accelerate the adoption of new methodologies and practices, the report also recommends constructing a completely open ecosystem where everyone, including the government and teachers, could cooperate and develop more valuable material. In addition, the professional learning of STEM teachers could be supported by partnering with industries and other organisations, modernising the STEM teachers' recruitment, and career management. European Schoolnet (2018) presents that one of the tools for professional learning could be online platforms, as an opportunity to exchange ideas with colleagues and experienced teachers. Furthermore, during professional learning, STEM teachers could be introduced to different teaching materials, such as prototyping (e.g. 3D printers), robotics equipment (e.g. robotics kit), and software (e.g. adaptation of mature open-source platforms for class management, content management, and school administrative services). Some project websites were provided by European Schoolnet (2018) to utilise for professional learning of STEM teachers, such as www.stem.vlaanderen.be, GEOMATECH project providing digital tools and interactive digital educational materials (e.g. GEOMATECH system, 3D printing methods, and mobile applications) for the classroom, and T^3 Europe network providing curriculum-related resources and webinars (www.t3europe.eu).

The report published by European Schoolnet (2018) highlighted the importance of in-service professional learning and creating partnerships with NGOs or industry in European countries to provide material support and external funding to develop teacher capabilities, STEM content and innovative purpose-built technologies and methodologies.

Approaches to Utilise in Professional Development

Many STEM teachers use traditional teacher-centred teaching in their classroom practices (Nistor et al., 2018) but the literature suggests there is a need to shift from traditional lecture-based teaching to inquiry, project-based, and problem-based learning (EL-Deghaidy et al., 2017). EL-Deghaidy et al. (2017) believe that such a shift in an interdisciplinary philosophy can improve deep conceptual understanding and 21st century skills. To do so, different approaches and practices, such as (a) production pedagogy, (b) instructional strategy, (c) inquiry, project-based, and problem-based learning approaches, (d) engineering design, and (e) technology-based approaches including learning platforms and the use of robotics, were recommended in many studies to utilise when supporting professional development.

Different approaches and practices that can be utilised for professional development;

- **Production pedagogy**
- **Instructional strategy**
- **Inquiry, project-based and problem-based learning approaches**
- **Engineering design**
- **Technology-based approaches including learning platforms and the use of robotics.**

Production pedagogy involves engaging pre-service teachers in teaching and learning activities directed to the production of socially valued artefacts to be shared with various audiences, such as a community of learners and online and/or local learning communities. Yanez et al. (2019) developed a Design Thinking (DT) course involving production pedagogy in Canada. During the DT course, pre-service teachers (1) were invited to produce something that is relevant to their personal and professional interests, aspirations and goals as STEM educators, (2) learned about and from the online community, and how they might contribute to the community knowledge-sharing dynamic (e.g. students would contribute a free-to-use asset that the community might build upon, use, or repurpose), and (3) created a prototype or artefact that expressed their own interests in relation to science and technology and contributed knowledge to the community. The authors found production pedagogy beneficial for pre-service STEM teachers' professional development as it encouraged students to take agentive roles in relation to inquiry, knowledge, and artifactual making, where actors do science differently in their own communities.

There is a range of instructional strategies that can be used for professional learning. Walan and McEwen (2018) investigated the views of teachers and principals on participation in a STEM competition as an **instructional strategy**. The principals facilitated the organisation around the competition and provided social support. During the study, teachers reported (1) the development of students' twenty-first-century skills, collaboration, (2) an increased interest of students in science and technology, (3) enhancement in teachers' teaching ideas and style linking to the curriculum. They advocate that STEM competition can be an instructional strategy for stimulating students' interest in learning STEM and supporting their development of problem-solving and critical thinking.

A culture of collaboration, the availability of a quality curriculum, using student-centred **inquiry** models of instruction, and well-organized and frequently available professional learning opportunities would improve teachers' effort to implement STEM pedagogy in their classrooms (Margot & Kettler, 2019). Margot and Kettler (2019) investigated what support teachers feel would improve their efforts to implement STEM pedagogy in their classrooms. The results showed that teachers believe school district support, guidance, and flexibility were necessary for STEM initiatives. Teachers perceive the engaging and authentic nature of interdisciplinary STEM education initiatives as potentially beneficial for students. Teachers also asserted that students benefit from hands-on, practical applications of STEM content providing in-depth problem-solving with authentic experiences. Margot and Kettler (2019) support the view that teachers must use questioning strategies to challenge students to support their higher-level cognitive thinking so that students reflect upon concepts and ideas in order to solve STEM challenges. However, to provide students with that, teachers should be skilled with the unique student-directed pedagogy. Their recommendations for practice include working together to create innovative ways to successfully integrate STEM education (Margot & Kettler, 2019). There may also be specific pedagogical needs within different settings that can be addressed with teacher in-service instruction. Another suggestion for future research involved investigating effective formative assessment strategies during STEM education. Teachers felt this was a missing component of STEM programs (Dare et al., 2014) to understand each student's progress throughout the unit. The role of the teacher is different in STEM, they have to provide project-based lessons that encourage critical thinking and innovation while building student understanding of content and concepts (Nadelson & Seifert, 2013). Nistor et al. (2018) found that three out of four of the surveyed teachers share a positive vision of innovative STEM teaching with their colleagues and head of school, and this is linked positively with the amount of innovation brought into the classroom.

This **project-based** student-centred approach in the STEM projects requires significant shifts in the way teachers envision curriculum and instruction and the way they structure the learning environment and process (Lesseig et al., 2017). The "Teachers Exploring STEM Integration" (TESI) approach to professional learning adopted a project-based approach and focused on STEM Design Challenges (DCs) such as designing and testing marshmallow towers or catapults, building a prosthetic limb, solving problems related to global climate change and colonizing Mars (Lesseig et al., 2017). These examples provide active and purposeful STEM learning opportunities for students while enabling teachers to take on a different role as co-learner versus knowledge provider enabling them to learn more about students' strengths and abilities they did not know before. One teacher stated that "Sometimes your lowest students, your least engaged students in the classroom, will excel the most in STEM projects.... Like all of a sudden, they come alive in these STEM projects" (Lesseig et al., 2017, p.17). During the planning and implementation of STEM DCs, teachers and the project team worked together using a range of instructional tools and resources which they found useful and effective. These instructional tools and resources included:

Teachers need opportunities to learn new ways to promote high-quality student interaction, help students develop STEM-based projects, and enhance their knowledge of STEM content, particularly of engineering design, since this content is underrepresented in middle school curricula.

Kennedy and Odell (2014); Lesseig et al. (2017)

- an overarching structure for engineering design to guide problem-solving activity
- the Claims-Evidence-Reasoning (CER) framework to promote argumentation
- strategies to facilitate cycles of inquiry, such as a "Question Wall" and a "Questions and Affirmations", which was a format for feedback
- support of 21st-century skills, such as creativity and teamwork

The participants learned about engineering design and completed a number of DCs with other STEM teachers and middle school students.

Engineering design (c.f. Figure 7 in Section 3.3) is highly recommended as a promising and accessible vehicle for integrated STEM education in school settings. However, educators have to understand the value and power of the engineering design process and know the content of the other disciplines to enable students to fail and persevere and feel capable of creating an educational environment that allows students to solve ill-defined problems as well as deepening their content knowledge (Margot & Kettler, 2019).

Kim et al. (2015) provide different tools and approaches to improve teachers' knowledge and confidence in the integrated STEM education, for example, place-based education approach, where the connection between students and their local, real-world environments were used (Adams et al., 2014), engineering design process (DiFrancesca, Lee, & McIntyre, 2014), and robotics (Bers, 2008).

As a technology-based approach, Kim et al. (2015) examined elementary teachers' STEM content knowledge as well as their preparation to teach STEM and found that while pre-service teachers were engaging in robotics activities actively and mindfully, their emotional engagement (e.g., interest, enjoyment) in STEM was also improved significantly. The results also indicated that the changes in participants' emotional engagement influenced their behavioural and cognitive engagement in STEM. However, they could not find any relationship between pre-service teachers' STEM knowledge and STEM engagement. The findings suggest that robotics can be used as a technology to enhance teachers' STEM engagement and teaching; however, teachers should be provided with professional learning before implementing this educational tool in schools. Likewise, Perritt (2010) probed professional development using a problem-based learning approach along with robotics and found that the more confident teachers were, the more they used robots and critical thinking in teaching.

> **Teachers need STEM knowledge to teach STEM content using robots; however, they have a lack of STEM knowledge, awareness of the benefits of using educational robotics and skills to use robotics in STEM education.**
>
> *Kim et al. (2015)*

The rapid development of technology will have an impact on teachers and researchers to improve or transform teaching and learning, so teachers should be familiar with a large set of available technology. Teachers and practitioners would benefit from a full range of technological tools available so that teachers and students can pick and choose what they need. Jeong et al. (2019) report on a meta-analysis about the effects of Computer-Supported Collaborative Learning (CSCL) in STEM education. The results indicate that the effects of CSCL may vary according to different variables and the contingencies that exist among these variables, which refers to who is using the tools and in what contexts. When providing information resources to students, they should be provided with appropriate resources for the learning topics, sufficient time to process them, and/or meaningful and engaging collaborative activities with the resources. However, above all teachers and practitioners should be provided with professional learning to be able to achieve these goals, manage the process of developing/applying tools, and orchestrate the pedagogical interventions in their classrooms.

> **Computer-Supported Collaborative Learning (CSCL) can be utilised in teachers' professional learning in STEM education.**

Assessment in STEM Education

This section addresses Research Question 5 and aims to examine how STEM education is assessed. More specifically, it explores how the knowledge, skills, and/or values are assessed in STEM education and the place of formative and summative assessments in integrated STEM education. This section just offers a brief perspective from the literature as Reports #3 and #4 in the ATS STEM series of five linked reports, focus in depth on assessment including formative digital assessment in STEM education.

3.5.1 Assessment Methods

Assessment is an undeniable core part of education for many reasons, not only its role to support the quality of education but also to provide validity and reliability of educational tools.

Assessments—from formative assessment at the classroom level to large-scale state assessment for accountability—have the potential to limit the extent to which integrated STEM can be incorporated into K-12 education (Honey et al., 2014). In addition, the type of pedagogical practices a teacher engages in also seems to influence what type of assessment practices are used. For example, Nistor et al. (2018) found that STEM teachers seem to be reporting a considerable amount of direct traditional instruction (79%) coupled with summative assessment approaches (79%). In addition, existing assessments tend to focus on knowledge in a single discipline or content knowledge alone giving little attention to the practices in the disciplines and applications of knowledge (Honey et al., 2014). Therefore, we should be careful about choosing a pedagogical approach that targets all STEM disciplines together while supporting the classroom assessment practices in a constructive environment. Formative assessment can provide this by interacting with students throughout the process and providing students with opportunities to reflect on their own learning. Furthermore, digital and networking technologies have the potential to expand the range of outcomes (e.g., progressions of integrated STEM learning) that can be measured (Honey et al., 2014). Therefore, the focus of the ATS STEM project is to investigate how digital formative assessment can be designed and utilised in STEM classroom settings across a range of different contexts.

How can We Assess?

There are many different ways of integrating technology into assessment practices. For example, Beller (2013) presented three ways of using technology in large-scale assessment contexts:

1. Facilitating the assessment of the domains that have traditionally been the focus in schools, namely reading, mathematics, and science, increasing validity and improving the assessment of aspects within these domains that have previously proven difficult to assess.
2. Assessing generic competences, such as skills related to Information and Communication Technologies (ICT) and other transferable skills related to managing and communicating information.
3. Assessing more complex constructs, also known as 21st century skills but not limited to creativity, critical thinking, learning to learn, entrepreneurship, problem-solving, and collaboration (Beller, 2013; Shute et al. 2016).

As mentioned by Beller (2013), assessing the skills and competences is highly important. This section aims to provide information about the assessment of (1) defining integrated STEM education, (2) core STEM competences, (3) curriculum integration of STEM education, and (4) teacher education in relation to STEM education.

Assessing Core STEM Competences

The assessment of (1) generic competences, such as skills related to digital technologies, (2) transferable skills related to managing and communicating information, and (3) 21st-century skills, such as creativity, critical thinking, learning to learn, entrepreneurship, problem-solving and collaboration, are of importance (Beller, 2013). Assessing core skills and knowing how to measure what students have learned is also involved in STEM education (Guzdial & Morrison, 2016).

Assessment of the development of some skills without requiring students to master the skills is highly important to help develop learning progressions (Guzdial & Morrison, 2016). Guzdial and Morrison (2016) investigated computer science (CS) education as part of STEM education by using Parsons Problems. A Parsons Problem asks students to solve a programming problem, then gives them all the lines of code that solve that problem, on tiles or "refrigerator magnets" (Morrison et al., 2016). Therefore, using Parsons Problems is recommended for assessing CS-related skills and competences, such as programming.

O'Leary et al. (2018) provide an overview of the current state-of-the-art in digital technology-based assessment, with particular reference to advances in automated scoring of constructed responses, the assessment of complex 21st century skills in large-scale assessments and innovations involving high fidelity virtual reality simulations. Although in the past decades, digital technology has been transforming assessment in terms of the constructs that can be measured and the types of environments in which assessments can take place, governments largely failed to harness the potential of digital technology to promote and measure the 21st century skills needed for economic prosperity, such as critical thinking and collaborative problem-solving (OECD, 2016). Even though there is a huge effort to promote 21st century skills and other 'competence-based' approaches in curricular frameworks and policy documents worldwide, the research on their assessment and practical efforts to assess them still lag behind (Adamson & Darling-Hammond, 2015). This is particularly true in the case of less cognitively-oriented skills, such as citizenship skills, and personal and social responsibility. However, there remains a need to critically evaluate the contribution of each new innovation in technology-enhanced assessment.

Integrating Digital Assessment in Assessment

Bennett (2015) outlines three 'stages' of the integration of digital technology into assessment in the curriculum: (1) the delivery of traditional assessments via computers, (2) the characterisation of technology-based assessment by incremental changes, including innovative item formats, the automation of various assessment processes and early attempts to improve the measurement of constructs (or aspects of constructs) that have proven difficult to measure using paper-and-pencil tests, and (3) incorporation of interactive performance tasks or simulations or their tendency to be "more integrated with instruction, sampling performance repeatedly over time". The most significant characteristic of these stages is that decisions about the design, content, and format are informed by competency models and general cognitive principles from the science of learning. Building on these stages, Bennet (2015) found Automated Essay Scoring (AES) very beneficial for large-scale and local assessment initiatives, especially those in which the stakes for test-takers are relatively low.

To analyse and categorise the content and context of integrated activities that might be incorporated within a school curriculum, a simple matrix can be used. English (2017) provided a sample STEM integration matrix (See Table 20).

Three stages of the integration of digital technology into assessment:

- **the delivery of traditional assessments via computers**
- **the characterisation of technology-based assessment by incremental changes**
- **incorporation of interactive performance tasks or simulations or their tendency to be "more integrated with instruction, sampling performance repeatedly over time.**

Bennett (2015)

Table 20: Sample STEM integration matrix (adapted from English, 2017, p.S8).

		Science	Technology	Engineering	Mathematics	Arts
Content	Primary			x	x	
	Supporting	x				
Context	Disciplinary		x	x		
	Background	Personal	Societal	Occupational	Historical	Other
			x		x	

There are different aspects of the learning process and the learner that can be assessed in the classroom, one of which is the students' self-efficacy. Self-efficacy is a good predictor of performance, behaviour, and academic achievement, particularly when teaching and learning STEM content (Kelley & Knowles, 2016). For example, Akcaoglu et al.'s (2018) study investigated whether fifth and sixth-grade students were able to write about the usefulness and relevance of what they were learning in their science class through self-generated reflections and to examine the impacts of this activity on students' value, utility value, and interest for science. After conducting the research for eight weeks, students in each class were randomly assigned to a control or treatment condition. The students completed a survey, and to analyse the survey, a rubric was developed to categorise the students' response levels. Four levels were identified as the categories (See Table 21).

Table 21: Students' response levels and description of the levels (adapted from Akcaoglu et al., 2018, p.72)

Levels	Description
Level 0	The students did not respond or their response did not include anything regarding an application.
Level 1	The application provided by the student was very generic.
Level 2	The student provided a specific application or a future career but the impact and the reason for the impact of the knowledge was not fully explained.
Level 3	The student provided a specific application or a future career and the impact and the reason for the impact of the knowledge were explained

Results provided initial evidence that the intervention was applied appropriately and helped effectively increase students' utility value for science. These levels in Table 21 could be utilised when developing assessment tools and rubrics to determine the student levels in STEM classes.

Teacher Education on Assessment in STEM Education

Assessment for learning should be central in teacher education to help teachers and academics to develop STEM teaching and learning practice further (Ralls et al., 2018). One way of supporting evaluators and researchers is through a common measurement system (CMS). The adoption of common measurement tools is representative of a systems approach to addressing problems in education. CMS can help evaluators by creating evaluation plans that contribute to positive change by formatively assessing project goals and providing timely feedback rather than just documenting change (Kramer, Parkhurst, & Vaidyanathan, 2009; Matsumura et al., 2002). CMS can also help researchers by empowering them to shift focus toward optimising learning environments by abandoning objective observer roles and controlled experiments for interventionist strategies and theory-based design with multiple iterations to optimise the design of learning environments (Saxton et al., 2014). The shift in evaluation and research priorities through CMS could significantly contribute to the transformation of STEM education. Saxton et al. (2014) examined the conceptualisation stage of the development of a CMS. The authors provided the Common Measurement Committee's highest-ranked evaluation criteria, which were listed in order of importance based on the partnership's highest-ranked priorities. These evaluation criteria presented in Table 22 can benefit the development of assessment tools.

Table 22: Common Measurement Committee's highest ranked evaluation criteria (adapted from Saxton et al., 2014, p.22)

Ranked Evaluation Criteria	Rationale for Each Criteria's Importance
Link between defined construct and instrument	In reviewing preexisting instruments, there was a potential pitfall of a lack of congruence between the PMSP prioritised construct and the construct the instrument was designed to measure. Great care was taken in to examine the alignment of PMSP construct to that of existing instruments
Validity and reliability evidence	In order to ensure that existing tools would produce high-quality data, evidence of validity and reliability were key in evaluating instruments
Potential for data use for formative/ reflective purposes	The PMSP's emphasis on the use of data to drive program improvement and educator decision-making made this criterion a high priority
Sustainability of data collection tools	The goal of the committee was that tools in the common measurement system would be able to be used in perpetuity by partnering organizations after the appropriate initial training on use of the tools
Relevance of data and/ or instrument across diverse contexts: formal and informal education settings	Given that the PMSP involves both formal and informal educational settings and that cross-organization learning is a key benefit to common measurement, the instruments and the data they produce must be applicable and useful in diverse settings
Feasibility: cost, data processing and management	In order for instruments to be useful, they must also be feasible for organizations to use, therefore, the cost, data processing and management associated with each instrument were considered

Paul, a lecturer in the School of Electronic and Electrical Engineering, expressed the difficulty he finds in assessing group work by stating that *"some things are very difficult to examine in a practical setting, like team work, group work and separating out individual contributions. … assessment is quite often is pass and fail and we judge success, not on how someone has approached the problem, but on the outcome…we could do a lot more assessment work around their approach to problem solving. … we are still not so great with assessment with practical work."*.

Ralls et al. (2018)

"An emphasis on what students can do with knowledge, rather than what units of knowledge they have, is the essence of 21st century skills." (Silva, 2009, p. 630). Saxton et al. (2014) also argue that assessing the application of concepts or conceptual knowledge in STEM is more important than testing knowledge recall to evaluate college and career readiness in STEM because it shows the ability to transfer understanding to new contexts and more accurately reflects the way concepts are applied in the real world by scientists, engineers, and other STEM professionals (Morrison et al., 2016). Even though constructed response items provide more detailed information about student ability levels, its analysis requires more time and therefore is more difficult to use effectively as formative assessments. The STEM CMS uses a combination of carefully designed multiple-choice and constructed-response items. In K-12 STEM education, science inquiry, engineering design, and mathematical problem-solving performance-based work samples are the most common ways of measuring cognitive skill constructs. The authors utilised performance-based written work samples with consistent, common tasks to assess the higher-order cognitive skills in the STEM CMS. Saxton et al. (2014) believe that the quality of performance-based assessment systems can be improved by rater training, calibration discussion, and teacher professional development focusing on assessment practices. They also indicate that there is a need to develop teacher practice measurement instruments that do not isolate STEM disciplines, feasible to use for large-scale and provide formative data to improve instructional practices. Teacher and informal educator practices which are the most important contributors to student STEM college and career readiness were identified as (1) pedagogical content knowledge, (2) instructional practices, and (3) supportive teacher-student relationships. Therefore, key beliefs, knowledge, and skill areas of educators should be measured to determine the effectiveness of professional development (PD). The partnership in Saxton et al. (2014) defined pedagogical content knowledge, instructional practices, and teacher self-efficacy as the professional development outcomes and measurement priorities.

Assessment Tools

The quality of delivery for formative assessments has an impact on the assessment itself. Once a formative assessment has been selected or created, plans must be made to ensure the implementation fidelity of the system. When developing this system, the process-oriented and self-regulatory nature of formative assessment and the ways of providing feedback should be taken into account. The way of providing feedback through digital tools plays should also be considered. Tools should be student-friendly. Students must be provided with adequate time to make use of any feedback given. Cognitive labs (i.e., questioning students or teachers during their use of specific tools) during the assessment system development phase of the project might be useful for this.

Additionally, the effectiveness or practicality of assessment tools is of importance. One of the widely acknowledged challenges in the context of STEM education is developing an assessment tool (Sergis et al., 2019). Sergis et al. (2019) designed a novel Teaching and Learning Analytics (TLA) tool, which aims to address a widely acknowledged challenge in the context of STEM education; they propose that using the TLA tool allows teachers to analyse their existing Inquiry-based Educational Designs (IEDs) in terms of tool-supported guidance, which is a significant factor for an effective IED delivery and relate these analyses to customisable students' educational data to facilitate the re-design process. Sergis et al. (2019) believe the importance of providing appropriate guidance by combining digital tools such as online labs and modelling tools in order to effectively engage students in inquiry tasks in STEM education.

Initial evidence indicates that the insights generated offer statistically significant indicators that impact students' activity during the delivery of these IEDs. A prime example of technologies used in this regard is online labs including virtual and remote labs (Zervas et al., 2015). These labs in STEM IED operated virtual or physical equipment and had the capacity to provide guidance to support students' engagement in the Inquiry tasks while fostering more "hands-on" learning experiences for students (De Jong, Sotiriou, & Gillet 2014). Sergis et al. (2019) believe that the reflective processes can be supported by exploiting the potential of emerging "Teaching and Learning" Analytics (TLA) methods and tools because the proposed method enables teachers to analyse and self-assess the level and types of tool-supported guidance they have provided before delivery, allowing for early-on (re)design. The tool can build student profiles that are directly related to the analysis of the IED that students engaged with. An overview of the TLA tool is provided in Figure 9.

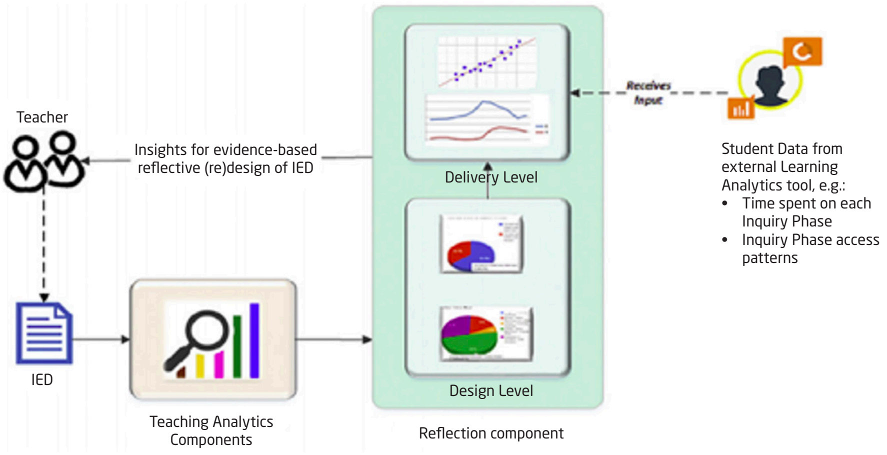

Figure 9: Overview of the proposed Teaching and Learning Analytics (TLA) tool (Sergis et al., 2019, p.728)

Sergis et al. (2019) are of the opinion that this TLA tool can facilitate teachers in the process of reflection and (re)design of their IED. To achieve this, educational analytics methods should support teachers with insights on how to systematically improve their teaching practice and provide more tailored and effective learning experiences to the students. By doing so, it can support teachers in analysing as well as evaluating their educational designs, based on data-driven insights. The results indicate that the proposed TLA method and tool generate insights that are significantly correlated with diverse aspects of students' activity during the Inquiry learning process, and thus could be used to support teacher inquiries. Accordingly, Sergis et al. (2019) recommend future studies should focus on conducting deeper longitudinal evaluation through teachers' inquiries in order to provide robust evidence on the added value of the TLA tool, especially in terms of improving teachers' reflection and enhancing students' engagement and performance in Inquiry-based STEM education.

CONCLUSION

This report is presented as part of the Erasmus+ project Assessment of Transversal Skills in STEM (ATS STEM), an innovative policy experimentation project being conducted across eight European Union countries through a partnership of 12 educational institutions. STEM education is a priority for all of the ATS STEM partners and each country/region is already engaged in implementing specific policy actions to promote the development of STEM knowledge and competences across their school sectors. The aim of the ATS STEM project is to design and develop STEM learning opportunities for students and assess student's transversal STEM competences using appropriate digital assessment methods.

This report discusses the findings of a systematic literature review and synthesis of journal publications over the period 2010-2019. The selection of literature for final inclusion in this review was informed by the identification of five research questions as deemed most relevant to the focus of the ATS STEM project, namely:

1. What are the different definitions of STEM education?
2. What are the core STEM competences?
3. What does an integrated STEM education curriculum look like?
4. How do teachers understand the learning domain and its perceived goals as well as the most appropriate way to organise learning activities?
5. What is assessed in STEM education?

The stages of the review process and the use of exclusion criteria were described in section two of this report. Overall, 79 publications were identified as relevant for inclusion in this review of published literature in STEM Education (presented in Appendix C). Section three presents the emergent themes from our analysis of the selected literature in terms of answering the five research questions posed.

Twenty distinct definitions of STEM education were found ranging from simple referencing of the four STEM disciplines; educational approaches at the intersections of any number of the four disciplines; to referencing all four STEM disciplines in an integrated manner (Bybee, 2013; Sanders, 2009). Analysis of these definitions revealed 23 sub-characteristics of STEM education that have been classified as the seven characteristics of integrated STEM Education: namely (1) Core STEM Competences; (2) Problem-Solving Design and Approaches; (3) Disciplinary and Interdisciplinary Knowledge; (4) Engineering Design and Practices; (5) Appropriate Use and Application of Technology; (6) Real-World Contexts; and (7) Appropriate Pedagogical Practices.

It is broadly recognised in the literature that integrated STEM education allows students to develop a range of transversal competences and it is highly important for STEM educators to foster the development of such competences (Bailey et al., 2015). This report uses the term Core STEM Competences as a collective term to examine what specific skills and competences may be developed in STEM Education (Question 2). Review of the literature identified 243 specific STEM skills and competences, which were classified into eight categories of core STEM competences: namely (1) collaboration, (2) problem-solving, (3) innovation and creativity, (4) critical thinking, (5) disciplinary skills and competences, (6) self-regulation, (7) communication and (8) metacognitive skills.

Students need these core STEM competences to deal with the complex and difficult everyday challenges/issues (Bailey et al., 2015). There is convincing evidence to demonstrate that STEM education strengthens student skills for transferring knowledge acquired between different contexts, as it focuses on real problems that students are familiar with (Sanders, 2009). This may also be attributted to the fact that the students understand more clearly why competences are important to learn through a programme that involves hands-on, project-oriented problem-solving techniques and appreciate the opportunities that STEM skills open for them (Bailey et al., 2015). Furthermore, it appears that STEM education contexts that focus on integrating all four STEM subjects improve student knowledge in the different STEM disciplines (National Academy of Sciences, 2014) and facilitates their connection.

The next question investigated how integrated STEM curricula have been designed and implemented in European classrooms. Nistor et al. (2018) reported on the main STEM education practices in Europe drawing on survey responses of 3,780 educators across 38 European countries. Their findings suggest that resources (including use of digital tools and resources), innovative pedagogies and curriculum innovation, are particularly important in encouraging a more integrative approach to STEM teaching. The process of integrating all STEM subjects in authentic contexts can be complex due to the lack of a cohesive understanding of STEM education (Kelley & Knowles, 2016). In contrast to traditional "segregated" STEM, integrated STEM requires the application of knowledge and practices from various STEM disciplines to solve complex and transdisciplinary problems (Struyf et al., 2019). Designing integrated experiences providing intentional and explicit support for students is important in order to build knowledge and skill both within the disciplines and across disciplines. However, the literature is clear that students' knowledge in individual disciplines must be supported. Connecting ideas across disciplines is challenging when students have little or no understanding of the relevant ideas in the individual disciplines. The general pattern is that science and mathematics are prominent with engineering and technology mostly neglected (Kelley & Knowles, 2016). A possible solution to this imbalance is to utilise technology and engineering design as a catalyst for STEM learning and to develop representations of real-world problems since technology and engineering involve real-life contexts.

The next question probed some of the challenges that teachers face in implementing integrated STEM education in terms of (1) pedagogical, (2) structural (3) curricular (4) teacher, and (5) external challenges. The recommendations of how to overcome these issues and challenges and facilitate student learning and development are clear. Teachers need to be engaged in professional learning experiences, work together with teachers from other disciplines to identify crosscutting content or skills to help teachers clear up their misunderstandings about other disciplines, and become familiar with current practices of an interdisciplinary curriculum including parallel, cross-disciplinary, and infusion models.

The final question briefly examined the role of formative and summative assessments in integrated STEM education. Several approaches for integrating technology into large-scale assessment contexts were reported (Beller, 2013). Although in the past decades, digital technology has been transforming assessment in terms of the constructs that can be measured and the types of environments in which assessments can take place, governments largely failed to harness the potential of digital technology to promote and measure the core 21st-century skills needed for economic prosperity (OECD, 2016). Only a couple of examples of tools and strategies that could be used by teachers in the STEM Classroom were reported and many studies highlighted the need to support teacher's own knowledge of appropriate assessment practices and tools for STEM Education.

The major implication of this review and synthesis of literature in STEM Education is it highlights the need to scaffold an integrated approach to designing STEM learning activities for students that will develop their core STEM competences. The promotion of STEM education would benefit from such a conceptual framework, which outlines the relationship between and practical integration of each of the four disciplines (Smith & Southerland, 2007). Such a framework with well-integrated instruction will provide opportunities for students to be active learners while encouraging them to use higher-level critical thinking and problem-solving skills and increasing retention (Stohlmann et al., 2012).

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APPENDIX A

Assessment of Transversal Skills in STEM (ATS STEM)
Erasmus+ Call reference: EACEA/28/2017
Terms of Reference for Work Package 1, Tasks 1- 4
Excerpts from the Original Proposal (See pages 61-65)

WP 1 - STEM Conceptual Framework

Work package 1 (WP1) sets the baseline for this project providing the theoretical and operational frameworks for the policy experimentations. It will result in a set of sharable outputs that illustrate a pathway to the improvement and modernisation of STEM education in schools in Europe within the partner countries to develop the skills of learners in the key areas of Science, Technology, Engineering, and Mathematics.

Task 1: STEM Education in Schools: What Research tells us

The initial task will involve:

- A review and synthesis of the research literature on STEM education with particular respect to schools, developing a set of inclusion and exclusion criteria level for the project scope.
- A mapping of the current state of the art of STEM education relevant to the project that provides an evidence base to highlight the areas that the policy implementations must address in particular with respect to key STEM skills for learners.

Output: A review and synthesis of the research literature on STEM education with particular respect to schools. In addition to a written report this output will include an executive summary of not more than one page comprehensible and accessible to each of the target stakeholders. A concise summary of the key takeaways of the full report will be produced for students, teachers, parents, policy makers and those in higher education, and industry concerned with STEM.

Task 2: How are Governments Addressing the Challenge of STEM Education? Case Studies from Europe?

This task will involve a focused review of the STEM education polices in each of the partner countries. This task will work to establish the key policy drivers at a national level that can effect change on a practical level in STEM education through targeted educational interventions.

Output: A review and synthesis of the research literature on STEM education with particular respect to schools. In addition to a written report this output will include an executive summary of not more than one page comprehensible and accessible to each of the target stakeholders. A concise summary of the key takeaways of the full report will be produced for students, teachers, parents, policy makers and those in higher education, and industry concerned with STEM.

Task 3: What is STEM (and how Do We Teach it)?

This task will build on the emergent findings of tasks one and two to develop an Integrated Conceptual Framework of STEM that marries findings from research literature with national policies to realise a shared understanding of STEM amongst the partnership that can also be communicated to external stakeholders.

Output: A report showing the result of the development of a conceptual framework for STEM education

Task 4: Review of digital assessment approaches: Digital Assessment of Learning of STEM Skills.

This will involve a review of relevant digital assessment approaches to determine which contemporary technology enhanced approaches are best suited to the teaching and learning of STEM. In particular, it will analyse and report on which approaches can enable:

- Problem-based and research-based learning
- Enquiry-based learning
- Collaborative learning
- Mobile learning

Output: A report that highlights best practice in digital assessment of core STEM Skills and competences. This report will primarily be targeted at the STEM researchers in higher education, policy makers and those in ICT leadership roles in schools.

APPENDIX B

List of 312 STEM education publications identified in literature review (2010-2019)

Akcaoglu, M., Rosenberg, J. M., Ranellucci, J., & Schwarz, C. V. (2018). Outcomes from a self-generated utility value intervention on fifth and sixth-grade students' value and interest in science. *International Journal of Educational Research, 87*, 67-77. doi:10.1016/j.ijer.2017.12.001

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APPENDIX C

79 publications selected for inclusion in the review of STEM education (2010-2019)

Author(s)	Year	Title of Publication	RQ
Akcaoglu M., Rosenberg J.M., Ranellucci J. & Schwarz C.V.	2018	Outcomes from a self-generated utility value intervention on fifth and sixth-grade students' value and interest in science.	5
Atkinson R.D.	2012	Why the current education reform strategy won't work	3,4
Aydin-Gunbatar S., Tarkin-Celikkiran A., Kutucu E.S. & Ekiz-Kiran B.	2018	The influence of a design-based elective STEM course on pre-service chemistry teachers' content knowledge, STEM conceptions, and engineering views.	1,4
Bartholomew S.R., Moon C., Ruesch E.Y. & Strimel G.J.	2019	Kindergarten student's approaches to resolving open-ended design tasks.	3,5
Bell D.	2016	The reality of STEM education, design and technology teachers' perceptions: a phenomenographic study.	4,5
Blackley S. & Howell J.	2019	The next chapter in the STEM education narrative: Using robotics to support programming and coding	1,2,3
Bybee R.	2013	The case of STEM education: challenges and opportunities	1,2,3,4
Corlu M.S.	2013	Insights into STEM Education Praxis: An Assessment Scheme for Course Syllabi	1,4,5
Corlu M.S., Capraro R.M. & Capraro M.M.	2014	Introducing STEM education: Implications for educating our teachers for the age of innovation	1,4
Dan Z.S. & Gary W.K.W.	2018	Teachers' perceptions of professional development in integrated STEM education in primary schools	4
Eguchi A. & Uribe L.	2017	Robotics to promote STEM learning: Educational robotics unit for 4th grade science	2,3,5
EL-Deghaidy H.; Mansour N.; Alzaghibi M. & Alhammad K.	2017	Context of STEM Integration in Schools: Views from In-service Science Teachers	2,4
English L.D.	2017	Advancing Elementary and Middle School STEM Education	3
English, L.D.	2016	STEM education K-12: perspectives on integration	2,3
Ercan S.; Bozkurt A.E.; Taştan B. & Dağ I.	2016	Integrating GIS into science classes to handle STEM education	4
European Schoolnet	2018	STEM Education Policies in Europe	3,4
Freeman S.; Eddy S.L.; McDonough M.; Smith M.K.; Okoroafor N.; Jordt H. & Wenderoth M.P.	2014	Active learning increases student performance in science, engineering, and mathematics	3
Fuesting M. A.; Diekman A. B.; Boucher K. L.; Murphy M. C.; Manson D. L. & Safer B. L.	2019	Growing STEM: Perceived faculty mindset as an indicator of communal affordances in STEM	4

Author(s)	Year	Title of Publication	RQ
Gardner M. & Tillotson J.W.	2018	Interpreting Integrated STEM: Sustaining Pedagogical Innovation Within a Public Middle School Context	3,4
Guzdial M. & Morrison B.	2016	Growing Computer Science Education into a STEM Education Discipline	5
Guzey S.S. & Moore T.J.	2015	Assessment of curricular materials for integrated STEM Education (RTP, Strand 4)	4,5
Guzey S.S., Moore T.J. & Harwell M.	2016	Building up stem: An analysis of teacher-developed engineering design-based stem integration curricular materials	2,4,5
Hallström, J. & Schönborn, K. J.	2019	Models and modelling for authentic STEM education: Reinforcing the argument	3
Hodges G.; Jeong S.; McKay P.; Robertson T. & Ducrest D.	2016	Opening Access to STEM Experiences One Day at a Time: Successful Implementation of a School-Wide iSTEM Day	1,2,3
Honey M.A., Pearson G. & Schweingruber H.	2014	STEM integration in K-12 education: status, prospects, and an agenda for research	1,2,3
Hudson P.; English L.D.; Dawes L.; King D. & Baker S.	2015	Exploring links between pedagogical knowledge practices and student outcomes in STEM education for primary schools	1,3,5
Ibáñez M.B. & Delgado-Kloos C.	2018	Augmented reality for STEM learning: A systematic review	3,5
Jagannathan R.; Camasso M.J. & Delacalle M.	2019	Promoting cognitive and soft skills acquisition in a disadvantaged public-school system: Evidence from the Nurture thru Nature randomized experiment	2,3,5
Jeong, H.; Hmelo-Silver, C. E. & Jo, K.	2019	Ten years of Computer-Supported Collaborative Learning: A meta-analysis of CSCL in STEM education during 2005-2014	3,4,5
Johnson, C. C., Peters-Burton, E. E. & Moore, T.J.	2016	STEM road map: A framework for integrated STEM education.	1,3,4
Kalaian S.A.; Kasim R.M. & Nims J.K.	2018	Effectiveness of Small-Group Learning Pedagogies in Engineering and Technology Education: A Meta-Analysis	4,5
Kelley T. R. & Knowles J. G.	2016	A conceptual framework for integrated STEM education	1,4
Kennedy T.J. & Odell M.R.L.	2014	Engaging Students in STEM Education	3,4
Kim C.; Kim D.; Yuan J.; Hill R.B.; Doshi P. & Thai C.N.	2015	Robotics to promote elementary education pre-service teachers' STEM engagement, learning, and teaching	2,4
Kurup M.P.; Li X.; Powell G. & Brown M.	2019	Building future primary teachers' capacity in STEM: based on a platform of beliefs, understandings and intention	2,4
Lamb R.; Akmal T. & Petrie K.	2015	Development of a cognition-priming model describing learning in a STEM classroom	1,3

Author(s)	Year	Title of Publication	RQ
Lesseig K.; Slavit D. & Nelson T.H.	2017	Jumping on the STEM bandwagon: How middle grades students and teachers can benefit from STEM experiences	1,2,3,4
Margot K.C. & Kettler T.	2019	Teachers' perception of STEM integration and education: a systematic literature review	3,4
Martin-Paez T., Aguilera D., Perales-Palacios F.J. & Vílchez-González J.M.	2019	What are we talking about when we talk about STEM education? A review of literature	1,2
Mohd Shahali E.H., Halim L., Rasul M.S., Osman K. & Zulkifeli M.A.	2017	STEM learning through engineering design: Impact on middle secondary students' interest towards STEM	1,3
Mohd Shahali E.H., Halim L., Rasul, S., Osman K., Ikhsan Z. & Rahim F.	2015	Bitara-Stem™ training of trainers' programme: Impact on trainers' knowledge, beliefs, attitudes and efficacy towards integrated stem teaching	2,4
Mohd Shahali E.H.; Halim L.; Rasul M.S.; Osman K. & Arsad N.M.	2019	Students' interest towards STEM: a longitudinal study	3
Moore T.J. & Smith K.A.	2014	Advancing the State of the Art of STEM Integration	1,3,4
Mustafa N.; Ismail Z.; Tasir Z. & Mohamad Said M.N.H.	2016	A meta-analysis on effective strategies for integrated STEM education	1,2,3
Nathan M. & Pearson G.	2014	Integration in K-12 STEM education: Status, prospects, and an agenda for research	1,4
Nistor, A., Gras-Velazquez, A., Billon, N. & Mihai, G.	2018	STEM Education Practices in Europe	3,4
Park M.H.; Dimitrov D.M.; Patterson L.G. & Park D.Y.	2017	Early childhood teachers' beliefs about readiness for teaching science, technology, engineering, and mathematics	4
Pearson, G.	2017	National academies piece on integrated STEM	3
Radloff J. & Guzey S.	2016	Investigating Preservice STEM Teacher Conceptions of STEM Education	1,4
Ralls D.; Bianchi L. & Choudry S.	2018	'Across the Divide': Developing Professional Learning Ecosystems in STEM Education	3,4,5
Rasul M.S.; Zahriman N.; Halim L. & Rauf R.A.	2018	Impact of integrated STEM smart communities program on students scientific creativity	2,3
Rippon S. & Collofello J.	2012	Engineers Serving Education: Bringing math and science to life in the K-8 classroom	3,4
Ritz J.M. & Fan S.C.	2015	STEM and technology education: international state-of-the-art	3,4
Ryu M.; Mentzer N. & Knobloch N.	2019	Preservice teachers' experiences of STEM integration: challenges and implications for integrated STEM teacher preparation	1,4
Sánchez Carracedo, F.; Soler A.; Martín C.; López D.; Ageno A.; Cabré J.; Garcia J.; Aranda J. & Gibert K.	2018	Competency Maps: An Effective Model to Integrate Professional Competences Across a STEM Curriculum	2,4

Author(s)	Year	Title of Publication	RQ
Sarican G. & Akgunduz D.	2018	The impact of integrated STEM education on academic achievement, reflective thinking skills towards problem solving and permanence in learning in science education	2,3
Saxton E.; Burns R.; Holveck S.; Kelley S.; Prince D.; Rigelman N. & Skinner E.A.	2014	A Common Measurement System for K-12 STEM education: Adopting an educational evaluation methodology that elevates theoretical foundations and systems thinking	2,4,5
Sergis S.; Sampson D.G.; Rodríguez-Triana M.J.; Gillet D.; Pelliccione L. & de Jong T.	2019	Using educational data from teaching and learning to inform teachers' reflective educational design in inquiry-based STEM education	3,4,5
Shahbazi Z., Jacobs M., Lehnes A. & Mancuso K.	2016	Designing integrated STEM education: Linking STEM teachers and learners in a k-20 continuum	3,4
Shaughnessy M.	2013	Mathematics in a STEM Context	1
Sheffield R.; Koul R.; Blackley S. & Maynard N.	2017	Makerspace in STEM for girls: a physical space to develop twenty-first-century skills	2,3
Shernoff D.J., Sinha S., Bressler D.M. & Ginsburg L.	2017	Assessing teacher education and professional development needs for the implementation of integrated approaches to STEM education	4
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Subbian, V.	2013	Role of MOOCs in integrated STEM education: A learning perspective	3,5
Thibaut L., Knipprath H., Dehaene W. & Depaepe F.	2018b	How school context and personal factors relate to teachers' attitudes toward teaching integrated STEM	1,4
Thibaut L.; Knipprath H.; Dehaene W. & Depaepe F.	2018a	The influence of teachers' attitudes and school context on instructional practices in integrated STEM education	1,2,3,4
Thibaut L.; Knipprath H.; Dehaene W. & Depaepe, F.	2019	Teachers' Attitudes Toward Teaching Integrated STEM: The Impact of Personal Background Characteristics and School Context	1,4
Thibaut, L., Ceuppens, S., De Loof, H., De Meester, J., Goovaerts, L., Struyf, A., Boeve-de Pauw, J., Dehaene, W., Deprez, J., De Cock, M., Hellinckx, L., Knipprath, H., Langie, G., Struyven, K., Van de Velde, D., Van Petegem, P. and Depaepe, F.	2018	Integrated STEM Education: A Systematic Review of Instructional Practices in Secondary Education	2,3,4
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Author(s)	**Year**	**Title of Publication**	**RQ**
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Vickrey T.; Rosploch K.; Rahmanian R.; Pilarz M. & Stains M.	2015	Research-Based Implementation of Peer Instruction: A Literature Review	4
Walan S. & McEwen B.	2018	Teachers' and principals' reflections on student participation in a school science and technology competition	2,4
Wang H.; Moore T.J.; Roehrig, G.H. & Park M.S.	2011	STEM Integration: Teacher Perceptions and Practice	1,2,3,4
Weintrop D.; Beheshti E.; Horn M.; Orton K.; Jona K.; Trouille L. & Wilensky U.	2016	Defining Computational Thinking for Mathematics and Science Classrooms	3,5
Wong G.K.W. & Huen J.H.M.	2017	A conceptual model of integrated STEM education in K-12	1,2,3
Wong, G.K.W.	2017	Integrative learning in K-12 STEM education: How to prepare the first step?	1,2,3
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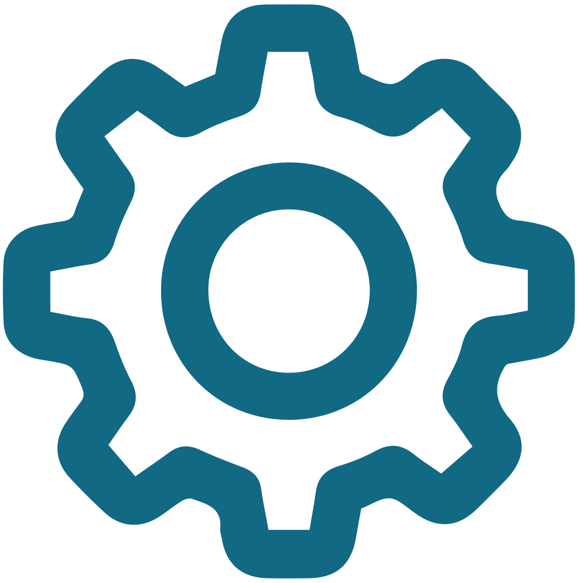
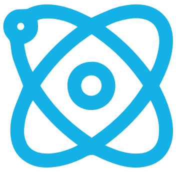
Zhou S.; Zeng H.; Xu S.; Chen L. & Xiao H.	2019	Exploring Changes in Primary Students' Attitudes Towards Science, Technology, Engineering and Mathematics (STEM) Across Genders and Grade Levels	3,5





APPENDIX D

Core Skills and Competences identified in STEM education (2010-2019)

	Problem-Solving	Communication	Innovation and Creativity	Critical Thinking	Meta-Cognitive Skills	Collaboration	Self-Regulation	Disciplinary competences
Wang et al. (2011)	Problem-solving			Critical thinking	Making connections with learning experiences			Mathematical (thinking) skills
Bybee (2013)	Problem-solving, Decision-making	Communication			Cognitive and meta- cognitive skills, Adaptability, Systems thinking		Self-management	
Honey et al (2014)		Communication	Innovation (innovative thinking), Taking an initiative	Critical thinking	Cognitive and meta- cognitive skills, Flexibility	Collaborative skills, Teamwork, interpersonal attributes, intrapersonal traits	Responsibility	Mathematical (thinking) skills, Technological skills
Saxton et al. (2014)				Reasoning, Argumentation	Cognitive and meta- cognitive skills			Scientific skills
Kim et al. (2015)	Problem-solving	Communication	Creativity	Critical thinking		Collaborative skills		Engineering design skills
Mustafa et al. (2016)	Problem-solving	Presenting		High order thinking skills		Collaborative skills		
Mohd Shahali et al. (2015)		Communication, Presenting	Creativity					
English (2016)	Problem-solving, Inquiry		Innovation (innovative thinking), Creativity	Critical thinking				
Guzey et al. (2016)		Communication						Engineering skills, Mathematical (thinking) skills

	Problem-Solving	Communication	Innovation and Creativity	Critical Thinking	Meta-Cognitive Skills	Collaboration	Self-Regulation	Disciplinary competences
Hodges et al. (2016)	Problem-solving		Creativity	Critical thinking, Analytical thinking		Collaborative skills, Teamwork		
Eguchi & Uribe (2017)	Problem-solving, Decision-making	Communication	Innovation (innovative thinking)	Critical thinking		Collaborative skills		Engineering skills, Mathematical (thinking) skills, Computing (computational) skills, Programming skills, Express themselves using the technological tool
EL-Deghaidy et al. (2017)	Problem-solving, Research		Creativity	Critical thinking, High order thinking skills	Cognitive and meta- cognitive skills	Collaborative skills		
Lesseig et al. (2017)	Problem-solving	Communication	Creativity	Critical thinking, Argumentation		Collaborative skills, Cooperative thinking		
Sheffield et al. (2017)	Problem-solving	Communication	Creativity	Critical thinking		Collaborative skills, Teamwork		
Wong (2017)		Communication			Flexibility	Teamwork, interpersonal attributes, Mutual respect, Courtesy, Ethical awareness	Responsibility, Positive attitude, Integrity	
Wong & Huen (2017)	Problem-solving, Inquiry, Creative problem-solving skills, Inference making, Hypotheses making, Seeking evidence		Innovation (innovative thinking), Making an invention, Creativity	Critical thinking, Logical thinking, Associative thinking, Convergent thinking, Divergent thinking				Technology literacy, Digital technology skills

	Problem-Solving	Communication	Innovation and Creativity	Critical Thinking	Meta-Cognitive Skills	Collaboration	Self-Regulation	Disciplinary competences
Sánchez Carracedo et al. (2018)	Problem-solving, Decision-making, Complex problem solving	Communication	Innovation (innovative thinking), Coming up with new ideas, Entrepreneurship	Critical thinking, Reasoning		Teamwork, interpersonal attributes, Leadership, Team building, Negotiation skills, Conflict resolution, personal skills	Responsibility, Appropriate attitude towards work, Autonomous learning, Sustainability and Social commitment	Theoretical learning, Practical skills, Numeracy skills, Computer skills, Information literacy
Sarican & Akgunduz (2018)	Problem-solving	Communication	Innovation (innovative thinking), Taking an initiative, Creativity	Reflective thinking skills, Critical thinking	Flexibility	Social and cultural skills	Self-control, Career and life skills	Scientific skills, Information literacy, Technology literacy
Thibbaut, Ceuppens et al. (2018)	Problem-solving	Communication	Innovation (innovative thinking), Creativity	Critical thinking		Collaborative skills		
Thibaut et al. (2018a)	Problem-solving, Dealing with information	Communication	Innovation (innovative thinking), Creativity	Critical thinking		Collaborative skills, Cooperative thinking		
Türk et al. (2018)	Problem-solving	Communication	Creativity	Critical thinking		Collaborative skills		
Walan & McEwen (2018)	Problem-solving	Communication		Critical thinking, Analytical thinking		Collaborative skills		

	Problem-Solving	Communication	Innovation and Creativity	Critical Thinking	Meta-Cognitive Skills	Collaboration	Self-Regulation	Disciplinary competences
Blackley & Howell (2019)	Problem-solving, Algorithmic problem solving, Non-routine problem solving	Communication	Creativity	High order thinking skills, Critical reasoning	Adaptability, Systems thinking	Collaborative skills, interpersonal attributes	Self-management, Self-development	Computing (computational) skills
Jagannathan et al. (2019)	Problem-solving, Decision-making, Asking questions and gathering information to solve problems	Presenting	Coming up with new ideas, Creativity			Leadership, Attentiveness, Being sensitive to others' feelings, Talking to others, Listening to others, Working with others	Being on time, Self-confidence, Self-discipline, Dependability, Trustworthiness, Always doing what you said you were going to do, Motivation, Perseverance, Working on their own, Not giving up on a task that is too hard to finish	Solving math problems, Testing ideas about science, Conducting science labs/experiments, Computer skills
Kurup et al. (2019)	Problem-solving, Decision-making, Making judgements	Communication	Innovation (innovative thinking), Creativity	High order thinking skills, Reasoning		Leadership		Digital literacy (e.g. writing code/analysing data)
Martin-Paez et al. (2019)	Problem-solving, Inquiry		Innovation (innovative thinking), Creativity	Logical reasoning		Cooperative thinking		Practical skills, Engineering skills, Technological skills
Struyf et al. (2019)	Problem-solving, Complex problem solving		Innovation (innovative thinking), Creativity	Critical thinking		Collaborative skills, Teamwork		

APPENDIX E

Practical classroom examples for STEM education (2010-2019)

Targeting STEM Discipline(s)	Real-Life Activity Example	Description	Authors
S, T, E, M	Bridge Design and Construction Activity involved the 2007 structural failure of the 35W Minneapolis Bridge in Minnesota and mentioned the need for constructing a new bridge in the same location as the collapsed one. Students are presented with two tables of data with the problem description; the first set of data involved key characteristics of four main bridge types, and the second table included two samples of each of the major bridge types with some of their key features.	Bridge Design and Construction Activity: English & Mousoulides (2015) implemented a STEM-based modelling activity in the sixth-grade, which was adapted from Guzey, Moore, & Roehrig (2010).	English (2016, 2017), English & Mousoulides (2015) based on Guzey, Moore, & Roehrig (2010)
S, T, E, M	Two project pages are recommended for real-life examples - I-TEST Project and TRAILS Project	Two projects, National Science Foundation I-TEST Project and TRAILS Project were mentioned in the paper which might provide some classroom activities of integrated STEM education.	Kelley and Knowles (2016)
S, T, E, M	Students work in small groups to complete a final project. The students design and build elaborate robots with papier-mâché costumes and moving parts made from recycled materials. They program their robot to accomplish the tasks that they set for themselves.	The authors worked with 4th grade students. In the 4th grade, students learn to integrate sensors into their programs. Working in pairs, students master the programming challenges that they set for themselves. Students not only learn how technology works, but they also apply the skills and content knowledge learned in school in a meaningful and exciting way. Students gain experience with the engineering design process while prototyping and that conform to real-world constraints. Their unique and completely student-created programs turn the creations into decision-making inventions.	Eguchi & Uribe (2017)

Targeting STEM Discipline(s)	Real-Life Activity Example	Description	Authors
S, T, E, M	Not provided	Ibáñez & Delgado-Kloos (2018) reviewed the literature on the use of augmented reality technology to support STEM learning. The review found that most augmented reality applications for STEM learning offered exploration or simulation activities. Eight of the AR applications reviewed, applications, such as augmented books (Gopalan et al., 2015), provided students with general ideas about a subject. In these augmented books, students can select the appropriate viewpoint for the 3D virtual models appearing out of the book pages (Billinghurst, Kato, & Poupyrev, 2001). Another application presented by Liou, Bhagat, & Chang (2016) allows students to explore basic materials knowledge by providing 3D interactive animations. When students touch the interactive models on the handheld device, more detail information about the model appears as well as interactive animations and videos. The review also showed that augmented reality learning activities can be part of blended instructional strategies such as the flipped classroom.	Ibáñez & Delgado-Kloos (2018)
S, T, E, M	Developing projects on "Health, Environment and Energy, and Smart Cities"	Many activities presented but not targeting all STEM disciplines at the same time. One project - Make Tomorrow for Turkey- did focus on all STEM disciplines. MATERIALS: Audio/video materials, word processors and web-based or computer-based simulations, Ardunio Uno toolset	Nistor et al. (2018)

Targeting STEM Discipline(s)	Real-Life Activity Example	Description	Authors
S, T, E, M	Students developed a robot with WeDo kits and visual programming software.	Blackley and Howell (2019) recommend educators to: (a) plan and develop intentional, integrated STEM activities at all education levels with accessibility to all students, (b) carefully consider the procurement of digital tools, (c) focus on skills and processes, (d) engage in authentic professional learning, (e) explore different platforms for integrated STEM education, such as Makerspaces, and (f) improve robust, explicit teaching of science, technology and mathematics. The authors also found following kits useful: WeDo 2.0, LEGO Mindstorms ® EV3 robots, and Edison robots. However, they do not recommend Spheros ®, LittleBits TM, MakeyMakey ® and Arduino ® for authentic integrated STEM education due to their limited scope for covering all of the characteristics of integrated STEM education	Blackley & Howell (2019)
S, T, E, M	- Studying simple machines to discover how a car works - Designing a project to prevent a neighbourhood raccoon from getting into his family's trashcan	A student raising the question about what could be done to prevent a neighbourhood raccoon from getting into his family's trashcan: The class analysed the situation and the trashcan in question then proposed creating a clip for the lid using a 3D printer. The students carefully measured and designed the clip. After printing, they discovered the clip would not stay attached to the can. At this point, they evaluated what modifications needed to be made in the design. Using 3D CAD software, the students made the changes and reprinted the trashcan clip. This time the clip worked to keep the lid attached to the trashcan and prevented further raccoon scavenging in his family's trash.	Margot & Kettler (2019)

Targeting STEM Discipline(s)	Real-Life Activity Example	Description	Authors
S, T, E, M	Developing a project involving an experimental design on a special STEM theme with a real-life context.		Zhou et al. (2019)
S, T, M	High school biology students imagine that they are scientists in the 1990s faced with the task of sequencing the entire human genome.	Faced with the task of sequencing the entire human genome. Students determined their technique for assembling the full DNA sequence. Then, the students write their procedure in pseudocode. Next, classmates swap algorithms, attempt to implement them, and provide suggestions for improvement in terms of clarity and efficiency (CT-MS Practice: Assessing Different Approaches/Solutions to a Problem	Weintrop et al. (2016)
S,T,M	To understand how atoms bond to form molecules, interpreting and interrogating models that represent how individual atoms participate in bonding (e.g. Lewis structure models), consequent bond angles in 3D space (e.g. ball-and-stick models), as well the associated molecular volume (e.g. space-filling models).	Hallstrom & Schonborn (2019) advocate that modelling in the form of visual representations is one way of operationalizing due to being both authentic and serving a crucial role in supporting STEM education. "For example, in a science domain such as chemistry, in order to understand how atoms bond to form molecules, it is necessary for students to interpret and interrogate models that represent how individual atoms participate in bonding (e.g. Lewis structure models), consequent bond angles in 3D space (e.g. ball-and-stick models), as well the associated molecular volume (e.g. space-filling models). In a technology education domain, models related to the drawing or visuo-spatial manipulation and representation of an artefact or design process are often engaged … In a mathematics domain, various models are used to highlight different conceptual interpretations of fractions, for example." Overall, the authors view modelling as an authentic practice in STEM education and therefore a fundamental component of STEM literacy (Gadanidis et al., 2017).	Hallstrom & Schonborn (2019)

Targeting STEM Discipline(s)	Real-Life Activity Example	Description	Authors
S,M,E	The Mars Colonization challenge was used. A brief motivational video clip on space travel was provided which prompts: ● NASA plans to have human presence on Mars in 2035. ● Its surface conditions and the likely availability of water seem to make it the most hospitable of the planets. ● What questions does this information raise in your mind? Your group should create at least 10 questions that come up in your minds. ● Choose your favorite 5 questions. Put those questions on the sentence strips and add them to the question wall. The Question Wall was revisited throughout the project as students answered some of the questions and generated others during their research. Second, a "Questions &Affirmations" format was utilized as a way for teachers and students to provide and receive feedback.	After students presented their work, the audience was charged with providing constructive feedback in the form of questions and affirmations. Affirmations needed to go beyond compliments to note positive aspects related to how the group communicated their design process and their use of mathematics or science concepts. Questions were meant to be genuine wonderings that the group might consider in further redesigns and also help students connect their learning to the needs of their community, businesses, and other potential stakeholders. This structure was an important vehicle in supporting continued inquiry and reinforcing science, mathematics, and engineering connections.	Lesseig et al. (2017)
E, M	The designing activities for both the students: Ask them to design a building with low floors, high ceilings and wide walls, and generate conceptual surprises. This can also include STEM based modelling activities linking with engineering design.	For example, in designing and constructing an earthquake-proof building, sixth-grade students displayed conceptual surprise as they discovered the contribution of the construction materials, their measurements and costs, the structural shapes chosen, and the engineering techniques used to strengthen and stabilize their building. Through the wide wall design, students were encouraged to share and communicate their learning not only within the classroom but beyond.	English (2017) based on Gadanidis et al. (2017)
S, M	An activity was designed for high school physics classrooms, where students investigated the laws of physics that govern video games. Depending on the selected game, students calculated the gravitational constant (e.g., in Angry Birds) and/or conservation of energy and momentum (e.g., in Asteroids).		Weintrop et al. (2016)

Targeting STEM Discipline(s)	Real-Life Activity Example	Description	Authors
S	Another activity was designed for high school chemistry lesson, where students used an interactive simulation to explore the relationships between macroscopic properties of gases—pressure, volume, and temperature—based on how these properties emerge from microscopic interactions (i.e., the motion of the gas particles and the interaction with the walls of the container).		Weintrop et al. (2016)
N/A	Students created designs based on three stories "Baa Baa Black Sheep", "Itsy Bitsy Spider" and "Little Boy Blue". They designed (1) a way for the black sheep and its master to separate the wool into three bags, (2) a way to stop the spider from climbing the water spout, and (3) a way to wake up Little Boy Blue when the sheep or cattle are wandering.	Authors conducted research with kindergarten students and utilised design processes (open ended design and design portfolios). This study shows that integrated STEM can even be applied with students at the very young age.	Bartholomew et al. (2019)
Different STEM discipline combinations	See Appendix 1 in Nistor et al. (2018)	Education practices in Europe	Nistor et al. (2018)

Targeting STEM Discipline(s)	Real-Life Activity Example	Description	Authors
	Elodea – A 5E Lab on Osmosis: Students were then divided into small groups and asked to explore what happens to the cells of Elodea plants in three solutions: pure water, 5% salt (5 g table salt [NaCl] per 100 mL solution), or 10% salt (10 g per 100 mL solution). (These were hypotonic, isotonic, and hypertonic solutions when compared with the Elodea plant.) Students were guided through the process of focusing the microscope and making a wet slide with a live Elodea leaf. Then they were given the opportunity to predict the results of placing the Elodea leaf in each solution. After collecting the data, students were encouraged to discuss in their groups what happened to the Elodea leaves and why they thought those changes occurred (the “think, pair, share” model). Initially, students were presented with a real-life story about a one-week-old calf named Clark. In the story, the owner of Clark, Cecil Bingston, called a veterinary clinic because Clark had diarrhea and was given 8 quarts of water in addition to his normal bottle of milk. He was lying down, nonresponsive and experiencing seizures. The message was clear: The students must help Clark, or he would die. This real-life story line served as a “hook” to grab students’ attention. Students worked in pairs to execute a variety of tasks that assessed content understanding and the application of critical-thinking skills. In the “Meet the Scientists” session, an artist, a computer programmer, and two University of Georgia science faculty members visited with students to answer their questions, give advice regarding their future academic planning, and discuss STEM career options. Thus, the aim of the session was to inspire and encourage students to pursue science in the future and to consider careers in the STEM fields.	Elodea – A 5E Lab on Osmosis: The Elodea lab began with a discrepant event that revealed students’ conceptualizations related to osmosis. The STEM team asked students what they thought would happen to “gummy bear” candies that were placed in pure water for 45 minutes. Students stated whether they thought the gummy bears would shrink, expand, or stay the same. They were also given the opportunity to justify their answers by verbally sharing them with the class. Most students agreed that the gummy bears would expand, but they were not sure why they would expand. The “Clark the Calf” case study is an interactive, three-dimensional, virtual learning environment. Here, students learn about osmosis while taking on a role of a health professional. They utilize. problem-solving and critical thinking skills that a scientist would use in real life to help save the calf.	Hodges et al. (2016)

APPENDIX F

Examples of projects and their targeting STEM knowledge for students (Pitt, 2009; Ritz & Fan, 2015)

Twelve STEM projects for students in grade one, grade two, and grade three

Week	STEM Projects	The descriptions of each project
1	Purple flour	Colour change by reaction with the iodine
2	Egg-beater	The operation and function of the gear
3	Tumbler	The knowledge of the gravity
4	Gyroscope	How does a gyroscope spin on a plane
5	Yo-yo	How does a yo-yo rotate in a vertical direction
6	Trailer	The mechanical structure of the automobile
7	Needle emitting pellets	The air pressure
8	Sandball	How to produce sound by the vibration
9	Pirate ship	The curvilinear motion
10	Bead floating on the water	The buoyancy
11	Crane	The lever rule
12	Robot arm	The elasticity

Twelve STEM projects for students in grade four

Week	STEM Projects	The descriptions of each project
1	Magic Balloon	Colour change by reaction with the iodine
2	Triangle stability and graphic reinforcement	The application of triangle and quadrilateral in daily life
3	Electric Fan	How does the circuit work
4	Equal-armed lever	the equal-armed lever
5	Colourful table lamp	How does the LED light work
6	Labor-saving lever	Learn the labor-saving lever
7	Caged Birds	The appliccation of the parallax
8	Laborious lever	Learn the laborious lever
9	Making a steelyard	The application of the lever in daily life
10	Compound lever	Learn the compund lever
11	Runaway spider	The application of the eccentric wheel
12	Lever comprehensive application	Learn the application of leverage prinicple

Twelve STEM projects for students in grade five

Week	STEM Projects	The descriptions of each project
1	Rainbow windmill	The integration of circuit and parallax
2	Fixed pulley and movable pulley 1	Learn simple fixed pulley and movable pulley
3	Rain alarm	The applicarion of the humidity sensor
4	Fixed pulley and movable pulley 2	How do fixed pulley and movable pulley work
5	Storm frog	How does the motor drive gears
6	Wireless power supply	Hoe is energy transmitted wirelessly
7	Rotation of the pulley	Learn the rotation of the pulley
8	Dryers	The application of the centrifugal force
9	Pulley acceleration and deceleration	Learn acceleration and deceleration of the pulley
10	Four-wheel drive (4WD)	How to make and electric trolley
11	Composite pulley drive 1	Learn the pulley drive
12	Composite pulley drive 2	The application of the pulley drive

Twelve STEM projects for students in grade six

Week	STEM Projects	The descriptions of each project
1	Laser alarm	The prinicple of laser alarm
2	Idler	the application of the idler in daily life
3	Track tank	How to make a track tank
4	Gear drive	How does the gear drive work
5	Electric carbon swing	The electromagnetic induction
6	Gear ratio	LEarn the transmission ratio of the gear
7	Energy conversion demonstrator	Learn the energy conversion
8	Crown gears	How do crown gears work
9	Speed regulator	Learn to make a speed regulator
10	Helical gears	How do helical gears work
11	Gravity trolley	The application of the gravity
12	Crown gears and helical gears	Learn the application of crown and helical gears

APPENDIX G

Issues, Challenges and Factors to Implement Integrated STEM Education

Issues, challenges and factors	Authors
Structural challenges *e.g., separate content courses, rigid bell schedules, and students having a mix of mathematics and science teachers.* Pedagogical challenges *teachers and students having a different way of learning.* Curricular challenges *i.e. the tension between needing to meet grade-level content standards for mathematics and science while maintaining the exploratory, real-world components of STEM challenges.*	Lesseig et al. (2017)
Methods to interest teachers in STEM subjects and teaching, such as place-based learning and robotics-based learning, have been studied but which methods worked or how they worked have been rarely reported (Adams et al., 2014; Bers, 2008). Engineering is often missing in teacher learning of STEM education (Adams et al., 2014). Benefits of educational robotics are not appreciated among the majority of teachers due to no learning opportunity (Pittí, Curto, Moreno, & Rodríguez, 2013). There is a lack of information and systematic evaluation of teacher education on robotics for teaching (Arlegui, Pina, & Moro, 2013; Osborne, Thomas & Forbes, 2010).	Kim et al. (2015)
Pedagogical challenges *applying STEM pedagogy requiring some fundamental shifts in how they establish classroom environments (including pedagogy, curriculum, assessment, support and training)* Curricular challenges *the integrated nature of STEM curriculum (particularly at the high school level), planning time* Structural challenges *typical school structures* Concerns about students *inadequate knowledge of STEM disciplines* Concerns about assessment *lack of quality assessment tools* Lack of teacher support *lack of resources*	Margot & Kettler (2019)
Lack of resources *many teachers lack resources needed to effectively implement inquiry-based STEM learning experiences in classrooms.*	Johnson (2006)

Issues, challenges and factors	**Authors**
Lack of time to teach STEM Lack of instructional resources Lack of professional development Lack of administrative support Lack of knowledge about STEM topics Lack of parental participation Reluctance of teachers to collaborate.	Park et al. (2017)
STEM as interdisciplinary *Teachers involved in the focus groups perceived that integration could happen between two subjects rather than a spectrum of disciplines.* STEM as linked to life (local/international) *Partnerships with industries and universities were included in teachers' responses. They were seen as locally and regionally useful for developing students' interest in STEM disciplines and careers through direct interaction with the STEM community in their daily life.* 21st century skills and careers in science *Teachers believe that the 21st century skills including thinking skills, collaboration, problem solving, and research skills could be useful for selecting careers in science.* PCK and STEM education *Teachers identified the need for pedagogical content knowledge to help implement STEM education.* STEM school culture *The STEM school culture requires collaboration among stakeholders and building a collaborative and supportive STEM Community. In this STEM school culture, the exchange of experience and constant dialogue between teachers and the administrator were highly emphasised. Teachers need support from other disciplines (e.g. mathematics, technology) and from the school.* Factors facilitating or hindering the implementation of STEM Education *Contextual factors:* *1.a. Internal factors: teachers' beliefs, capacity and pedagogical knowledge and skills* *1.b. External factors: administrative support, collaboration amongst teachers, resources/ facilities, science curriculum content, class capacity, time issues, student and parent awareness of what STEM is, and the existence of a teacher guidebook and professional development (i.e. lack of teachers' preparedness)*	EL-Deghaidy et al. (2017)

ATS STEM