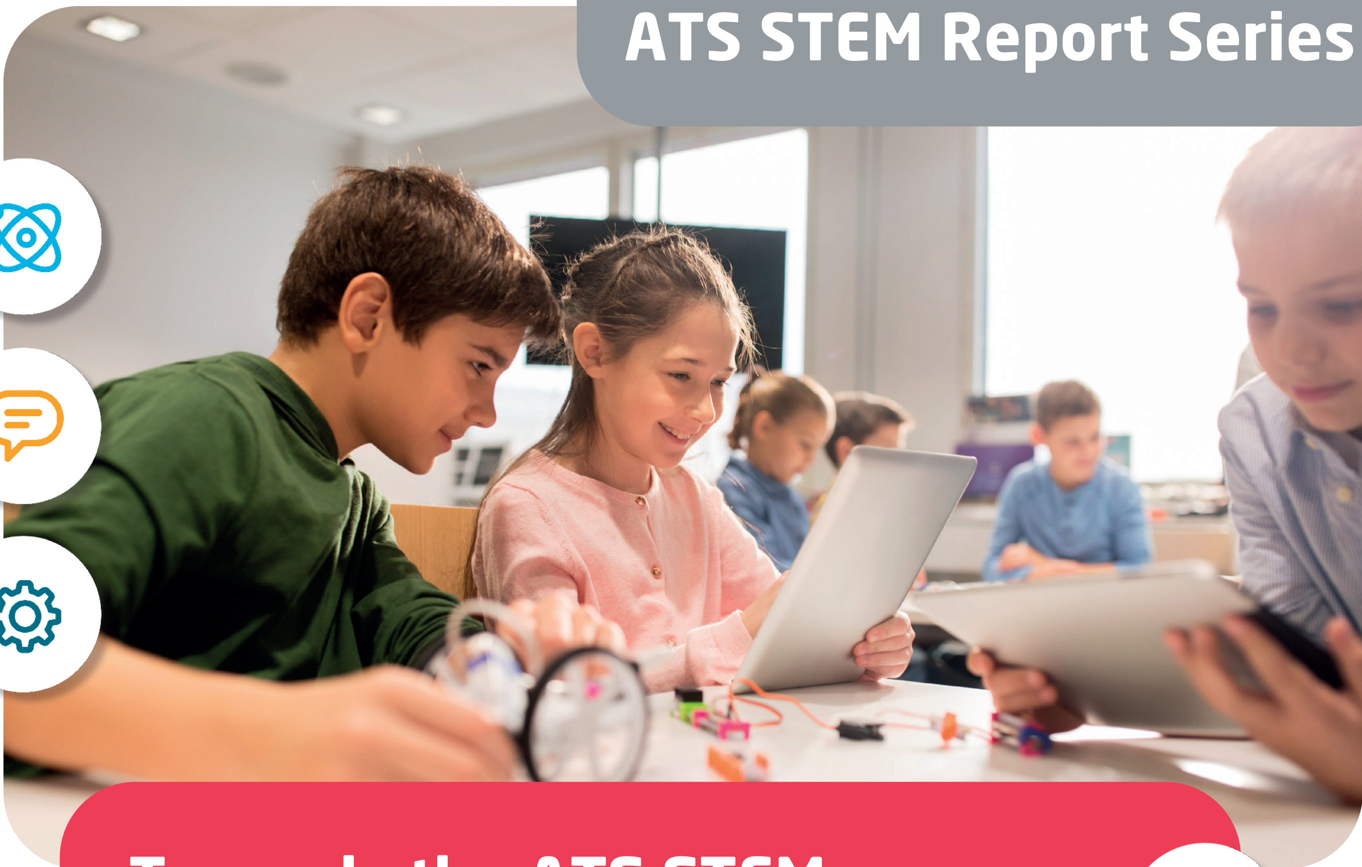
ATS STEM

Report #5 of
ATS STEM Report Series



Towards the ATS STEM Conceptual Framework

Deirdre Butler
Eilish McLoughlin
Michael O'Leary
Sila Kaya
Mark Brown
Eamon Costello

www.atsstem.eu #atsstem @stem_ats

Co-funded by the Erasmus+ Programme of the European Union

Please cite as: Butler., D., McLoughlin E., O'Leary, M., Kaya, S., Brown, M. & Costello, E. (2020). Towards the ATS STEM Conceptual Framework. *ATS STEM Report #5*. Dublin: Dublin City University. **http://dx.doi.org/10.5281/zenodo.3673559**

This is Report #5 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

ISBN: 978-1-911669-06-7

Typesetting, design and layout by

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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

The feedback from many colleagues on the ATS STEM project on various drafts of this report is gratefully acknowledged. Katherine Reynolds and Olivia Szendey are acknowledged for their contribution to the ATS STEM conceptual framework arising from the inputs of Reports #3 and #4 and Sinead Eccles who contributed to report#1. Prajakta Girme is thanked for her help in preparation of the final manuscript.

EXECUTIVE SUMMARY

This report (Report #5) 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 four deliverables in two work packages of ATS STEM project, as outlined in Appendix A—namely *STEM Conceptual Framework* (WP1) and *STEM Formative Digital Assessment Approach* (WP2)

This report is the fifth in a series based on deliverables related to the ATS STEM project. Reports #1 and #2 are concerned with the research pertaining to STEM education in schools and with national policies for STEM in various European countries, respectively. The third report, Report #3, discusses the key ideas and principles underlying formative assessment theory and presents the current state of the art with respect to how STEM digital formative assessment is conceptualised and leveraged to support learning of transversal skills in STEM. Report #4 examines the potential of various technology-enhanced tools and architectures that are used to support assessment for learning. Drawing on all four of these reports, Report #5 presents an integrated conceptual framework for the assessment of transversal skills in STEM.

In recent years, STEM education has become a high priority for governments and educational policy-makers around the world as it is believed to be crucial to the future global economic prosperity. The key underlying assumption is that countries with dynamic economies tend to be those with effective education systems that prioritise STEM education. However, STEM is a contested concept, context specific, with different drivers and constraints in different socio-political contexts. There are deep systemic issues facing many educational systems in order to help students to understand how to solve real-world problems using knowledge gained through STEM disciplines.

The basic premise of this report is that some of these systemic issues could be alleviated by policy-makers adopting a coherent conceptual framework that outlines the relationship between and the practical integration of each of the four disciplines of Science, Technology, Engineering and Mathematics (STEM). In addition, the role of assessment needs to be considered with guidelines developed for effective formative and summative assessments which effectively leverage the use of digital technologies, Such an integrated conceptual framework for STEM education is long overdue and likely to have major implications for how teachers understand the learning domain and its perceived goals as well as the most appropriate way to design and develop teaching, learning, and assessment activities.

The research underpinning the ATS STEM Conceptual Framework presented in this report provides a conceptual tool to help European educators reach a common understanding of what integrated STEM education is and how it can be assessed using a range of digital tools in schools. The report outlines and discusses the four essential components for designing and assessing integrated STEM topics in STEM education:

- Core STEM Competences
- STEM Learning Design Principles
- Formative Assessment STEM Tasks
- Digital Assessment Tools

Core STEM Competences
In the ATS STEM project, we consider the opportunity to develop a broad range of learning goals as essential to STEM education. In Report #1, we identified 243 specific STEM skills and competenc(i)es and further classified these into eight categories, namely: problem-solving, innovation and creativity, communication, critical-thinking, meta-cognitive skills, collaboration, self-regulation, and disciplinary competences, and identified them collectively as Core STEM Competences.

STEM Learning Design Principles
Integrated STEM education approaches should require students to apply disciplinary and interdisciplinary knowledge of mathematics, technology, science engineering and design. This integration of knowledge areas involves obtaining a final product or solution 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 skills both within the disciplines and across these disciplines. Six essential learning design principles are proposed in this framework for achieving integrated STEM education, i.e., Problem Solving Design and Approaches, Disciplinary and Interdisciplinary Knowledge, Engineering Design and Practices, Appropriate Use and Application of Technology, Real World Contexts and Appropriate Pedagogical Practices.

Formative Assessment STEM Tasks
In the literature, five key strategies to support the formative assessment process predominate. They involve clarifying and sharing learning intentions and success criteria; eliciting evidence of learning through classroom discussions, questions, and tasks; providing feedback that moves learners forward; peer-assessment and self-assessment. Formative assessment in STEM can present its own special challenges with respect to content domain definition. In designing formative assessments, a key principle to follow is that if a formative assessment does not support student learning, then it cannot be said to be valid for its intended purpose. Thus, attention to student learning that occurs as a result of formative assessment is an essential part of a validity argument in support of it. This element emphasises the importance of embedding approaches that enable problem/research-based learning, inquiry-based learning, collaborative learning and mobile learning in STEM education.

Digital Assessment Tools
In planning for technology-enhanced formative assessment in STEM education consideration must be given to what pedagogies are suitable for integrating teaching, learning and assessment in classroom practice. Several models for framing digital formative assessment have been proposed in terms of what technological knowledge and skills are required by teachers and students for implementation of technology-enhanced formative assessment practices and what technological functions can be integrated with formative assessment.

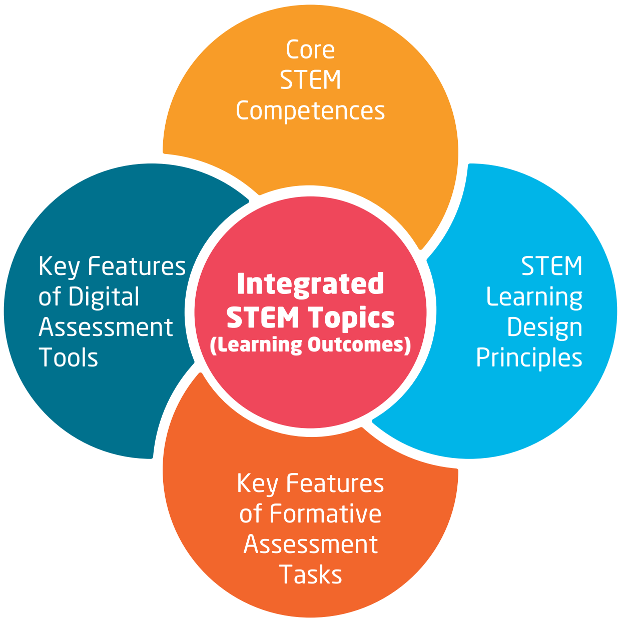


Figure 1. ATS STEM Conceptual Framework for Integrated STEM Education

These four components are combined in the ATS STEM Conceptual Framework which aims to inform the classroom practices of integrated STEM education topics and their assessment. Educators can benefit from such a conceptual framework encapsulating the key ideas from the literature. This framework has considerable potential to inform and deepen their understanding of what STEM education is as well as shaping and scaffolding their subsequent classroom practice.

This framework is not final. It remains a provisional piece of work that will be tested and validated by researchers and teachers in schools. A revised framework will then be developed. As such it remains a living rather than a reified artefact as we aim to plot a way forward towards a revised ATS STEM conceptual framework.

INTRODUCTION

In recent years, STEM education has become a high priority for governments and educational policy-makers around the world as it is believed to be at the heart of future global economic prosperity (e.g., Martin-Paez, Aguilera, Perales-Palacios & Vílchez-González, 2019; Thomas & Watters, 2015). A number of competing and co-existing drivers or rationale are used to promote an investment in STEM education initiatives, including social, environmental and/or economic development (Kelley & Knowles, 2016). Although an economic imperative to enhance global competitiveness underpins much of the discourse (Corlu, Capraro, R. M. & Capraro, 2014), other drivers include fostering innovation (Corlu et al., 2013; Sanders, 2009), addressing the low number of STEM graduates (European Schoolnet, 2018), and attracting STEM students for employment market (European Schoolnet, 2018; Nistor, Gras-Velazquez, Billon & Mihai, 2018). There is increasing recognition within the labour market of imminent shortages of STEM workers at all levels. For example, it is estimated that demand for STEM professionals and associate professions is likely to increase by 8% between now and 2025, much higher than the average 3% growth forecast for all occupations. (European Commission, 2015). Most countries are now aware of these imminent shortages and are taking steps to address this situation. A number of researchers, however, point out some of the failures and systemic issues facing educational systems in order to help students to understand how to solve real-world problems using knowledge gained through STEM disciplines (Bybee, 2013; National Governors Association, 2007; Ritz & Fan, 2015).

The basic premise of this report is that these systemic issues could be alleviated by policy-makers within STEM education adopting a coherent conceptual framework that outlines the relationship between and the practical integration of each of the four disciplines (Smith & Southerland, 2007). It follows that such a framework should be a priority for all policy-makers within STEM education. The challenge is to develop a framework that better presents the relationship between and the practical integration of each of the four STEM disciplines within STEM education. A framework such as this will have major implications for how teachers understand the learning domain 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. Educators can benefit from such a conceptual framework encapsulating the key ideas from the literature and that helps to inform their understanding and subsequent classroom practice. There is some early stage work underway in this area in the US but we need something similar at a European level (Kelley & Knowles, 2016).

This report begins by outlining existing frameworks for STEM Education and then presents The ATS STEM Conceptual Framework which draws on key findings from linked reports of the ATS STEM project (c.f. Appendix A) which serve to contextualise this proposed integrative framework for STEM Education in schools.

- Report #1: *STEM Education in Schools: What Can We Learn from the Research?* is an extensive literature review to investigate current understandings and practices internationally of STEM education in schools.
- Report #2: *Government Responses to the Challenge of STEM Education: Case Studies from Europe,* establishes the wider policy context across Europe.
- Report #3: *Digital Formative Assessment of Transversal Skills in STEM: A Review of Underlying Principles and Best Practice,* discusses design issues related to the implementation of formative assessment using digital technology.
- Report #4: *Virtual Learning Environments and Digital Tools for Implementing Formative Assessment of Transversal Skills in STEM*, examines the potential of various technology-enhanced tools and architectures that might be used to support assessment for learning in STEM.

EXISTING STEM EDUCATION FRAMEWORKS

This section describes a range of existing STEM education frameworks reported in the literature which informed the development of the ATS STEM Conceptual Framework and builds on literature review of Report #1 (McLoughlin, Butler, Kaya & Costello). This review identified seven core characteristics and eight core competences of STEM Education that helps develop a common understanding of the core dimensions of an integrated STEM education approach.

An underlying assumption of this ATS STEM Conceptual Framework is that visual models and representations for education can help effectively communicate what is understood by a particular concept and/or definition of a key term. In the context of STEM education these visual representations vary from viewing "STEM" as a single subject or discipline to considering STEM as completely transdisciplinary, or more associated with its real-world application (Bybee, 2013).

Despite the number of existing models and frameworks, there remains a need for a clearly conceptualised STEM Education Framework that presents an integrative perspective. We know from the literature that visual representations can help maintain attention and motivation (Cook, 2006), add information not easily conveyed by text alone (Mayer et al., 1996), and increase what is learned through connected text (Peeck, 1993). Educators can consequently benefit from well-designed visual conceptual frameworks as they can help to encapsulate key ideas that inform their new and emerging understandings and subsequent classroom practices. Therefore, there is a strong argument for developing a visual representation of a conceptual European framework for STEM education which provides a common language and shared understanding for both coordinating and implementing national STEM initiatives (Nistor et al., 2018). Such a framework arising from a comprehensive review of the literature has potential to advance a more integrated and research-informed approach to STEM education that supports curriculum reform.

Our analysis of the reviewed literature revealed 10 pre-existing frameworks for STEM education. Put another way, 8% of the 79 publications identified in the literature review, either developed or referred to a visual framework for STEM education. These frameworks and the corresponding authors are presented in Table 1: Overview of frameworks in STEM Education, along with an analysis indicating if they address the seven core characteristics of STEM education, as identified and discussed in the literature review (Report #1).

i. Core STEM Competences
ii. Problem Solving Design and Approaches
iii. Disciplinary and Interdisciplinary Knowledge
iv. Engineering Design and Practices
v. Appropriate Use and Application of Technology
vi. Real World Contexts
vii. Appropriate Pedagogical Practices

Furthermore, an example framework for each of these seven characteristics of STEM education identified in the literature review is provided in Appendix B. It should be noted that each of these frameworks only focus on and/or describe some of the identified core characteristics of STEM education. In particular, they do not present an integrated model for advancing STEM education in a manner consistent with the findings of the literature review in Report #1. Therefore, the focus of this report (#5) is to develop a policy and research-informed framework that combines the elements of teaching, learning and assessment to enable the design and development of integrated STEM curriculum and classroom practices with a particular focus on digital formative assessment.

Table 1: Overview of frameworks in STEM Education

Framework name	Developed by	Used by	Core STEM Competences	Problem Solving Design and Approaches	Disciplinary and Interdisciplinary Knowledge	Engineering Design and Practices	Appropriate Use and Application of Technology	Real World Contexts	Appropriate Pedagogical Practices
Descriptive framework showing general features and subcomponents of integrated STEM Education	Honey, Pearson and Schweingruber (2014, p.32)	Nathan & Pearson (2014)	X	X	X				X
Graphic of conceptual framework for STEM learning	Kelley and Knowles (2016, p.4)		X	X	X	X	X	X	X
Conceptual framework of Bitara-STEM: Science of Smart Communities	Mohd Shahali, Halim, Rasul, Osman and Zulkifeli (2017, p.1195)		X	X	X	X	X	X	X
Bitara-STEM: Science of Smart Community Module Development Process Conceptual Framework						X	X	X	X
Pedagogical knowledge practice framework	Hudson, English, Dawes, King and Baker (2015, p.136)		X	X	X				X
Theoretical framework for instructional practices in integrated STEM	Thibaut et al. (2018, p.8)	Struyf, De Loof, Boeve-de Pauw and Van Petegem (2019)	X	X	X	X			X
CER framework for science explanations	McNeill and Krajick, (2012)	Lesseig, Slavit and Nelson(2017, p.19)	X	X	X				
Theoretical framework for teachers' attitudes toward teaching integrated STEM	Thibaut, Knipprath, Dehaene and Depaepe (2018b, p.635)	Thibaut, Knipprath, Dehaene and Depaepe 2018a, p.194)	X						X
Framework for Integrated STEM Development	Blackley and Howell (2019)						X		
Conceptual framework of future primary teachers' platform of capacity to deal with STEM in their future teaching	Kurup, Li, Powell and Brown (2019)		X	X	X				

ATS STEM CONCEPTUAL FRAMEWORK

This section introduces and visualises the ATS STEM Conceptual Framework, which considers what learning outcomes can be achieved and assessed using a topic based integrated approach to STEM education.

The key finding of Report #2: *Government Responses to the Challenge of STEM Education: Case Studies from Europe,* is a dearth of developed policies in relation to STEM education; in fact, only four of the project partner countries - Flanders, Ireland, Austria and Cyprus - reported having a framework or policy (Costello, Girme, McKnight & Brown, 2020). In Europe, over the past decade our way of living, earning, and learning has been impacted by digital transformation. The transformative nature of new digital technologies is expected to continue over the next decade, particularly driven by developments in Artificial Intelligence (AI), with major implications for the future of work. In the future, new skills will be required as governments and employers seek to promote jobs, growth, and global competitiveness. Set against this backdrop, Report #2 explored how governments of European regions and countries are addressing the challenges posed of using digital tools to formatively assess STEM skills. The report first outlined the scope, objectives and methodology of the scoping work and summarised primary concepts in relation to STEM education. Via desk based research, a synthesis of relevant literature relating to national and international policies was made. After establishing that a handful of national policy initiatives exist reflecting a holistic or integrative perspective, the report describes the development of a scoping survey to assess the current state of STEM education policies in a sample of countries in Europe (those of the project partnership). Through the combination of desk research and this European scoping survey, the report highlighted best practices, common approaches, and dissimilarities in STEM Education. In particular, the report discusses areas where policy-makers and educators can take an integrated approach to STEM Education for the development of core transversal skills and competences for the next decade and beyond. In doing so the report aims to help plot a way toward a common understanding of STEM education for future developments in both theory and practice, using the European countries and regions involved in the ATS STEM partnership as an example.

The findings of Report #2 clearly demonstrates that there is a very uneven landscape of STEM education policy development across Europe with some countries having well-articulated and developed policies and some countries none at all. Moreover, the definition or understanding of what STEM actually is can vary greatly. This comes on top of the highly contextual nature of education itself, and the varying practices of teacher professional development with regards to STEM and STEM constituent subjects which the report highlighted. Encouraging female participation and attainment, is a strong theme across Europe and together with perceived skills gaps, are key drivers of STEM education policy. Although STEM education has a strong tradition of, and emphasis on equality there are a lack of specificity with regards to under-represented groups compared to other international policies analysed. The large agreement of the need for transversal skills competences in students; with the contested nature of STEM, and the context dependant nature of education across European schools, all point towards a need for an overarching framework. Such a STEM education skills framework would act as a mediating tool. It should allow teachers from across Europe to talk to each other about their STEM education practices but also provide an interface to conversations between, researchers, parents, STEM Industry experts and European citizens at large.

Therefore, the ATS STEM Conceptual Framework as depicted in Figure 2 was developed to illustrate the relationship between and the practical integration of each of the four STEM disciplines within STEM education, as well as considering the role of assessment particularly formative digital assessment. This framework also helps teachers understand the learning domain and its perceived goals as well as the most appropriate way to organise and assess learning tasks. The ATS STEM framework supports developing and assessing learning outcomes for integrated STEM topics by considering four components:

- Core STEM Competences
- STEM Learning Design Principles
- Key Features of Formative Assessment Tasks
- Key Features of Digital Assessment Tools

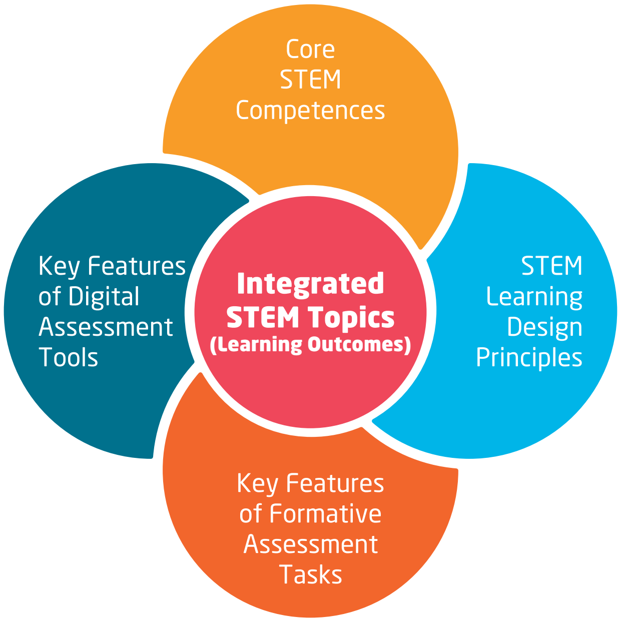


Figure 2. Towards the ATS STEM Conceptual Framework

Report #1 STEM Education in Schools: What Can We Learn from the Research? (McLoughlin, Butler, Kaya & Costello, 2020) informed the first two components of the ATS STEM Conceptual Framework. Report #3 Digital Formative Assessment of Transversal Skills in STEM: A Review of Underlying Principles and Best Practice (Reynolds, O'Leary, Brown & Costello, 2020c) informed the third component and Report #4 Virtual Learning Environments and Digital Tools for Implementing Formative Assessment of Transversal Skills in STEM (Szendey & O'Leary, 2020) informed the final component of the ATS STEM Conceptual Framework.

The findings of Report #1 highlighted a wide range of different definitions of integrated STEM education demonstrating diverse understandings with varying emphasises on different aspects. A synthesis of these definitions revealed 23 sub-characteristics related to integrated STEM Education, as described in Report #1. These were further distilled into seven core characteristics of integrated STEM Education:

i. Core STEM Competences
ii. Problem Solving Design and Approaches
iii. Disciplinary and Interdisciplinary Knowledge
iv. Engineering Design and Practices
v. Appropriate Use and Application of Technology
vi. Real World Contexts
vii. Appropriate Pedagogical Practices

The first characteristic, Core STEM Competences is one of the four components of the ATS STEM Conceptual Framework (Figure 2). The other six characteristics are combined to articulate the STEM Learning Design Principles of the ATS STEM Conceptual Framework.

The other two components of the ATS STEM Conceptual Framework, Key features of Formative Assessment Tasks and Key Features of Digital Assessment Tools, were informed by a targeted review of literature. The development of the component Key Features of Formative Assessment Tasks was informed by work undertaken to review the literature on (i) key ideas and principles underlying formative assessment theory and (ii) the current state of the art with respect to how STEM digital formative assessment is conceptualised and leveraged to support learning in STEM. Here, particular attention is paid to approaches that enable problem/research-based learning, enquiry-based learning, collaborative learning and mobile learning. This material is contained in Report #3.

Report #4 examined the potential of various technology-enhanced tools and architectures that can be used to support assessment for learning in STEM. Conclusions from this report guided the development of the ATS STEM conceptual framework's fourth component - Key Features of Digital Assessment Tools.

Each of the four components of this framework are discussed in further detail in the following sections.

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 policy makers over the past two decades (e.g. Griffith and Care, 2010; European Commission 2007; European Commission 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 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 skilful generally refers to carrying out some action with a degree of proficiency, doing it well rather than poorly - implying that there are degrees of skilfulness, and that skills can be learned and improved. However, using the term skills or even key skills can often be interpreted as reductionist and not fully capturing what it is meant to carry out these actions well (Mc Guinness, 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 DeSeco, Executive Summary, 2005, p. 4)

At 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 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 DeSeco, 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 competence. 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 2: Definition of 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 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 Figure 3:

- Problem-solving
- Innovation and creativity
- Communication
- Critical-thinking
- Meta-cognitive skills
- Collaboration
- Self-regulation
- Disciplinary competences

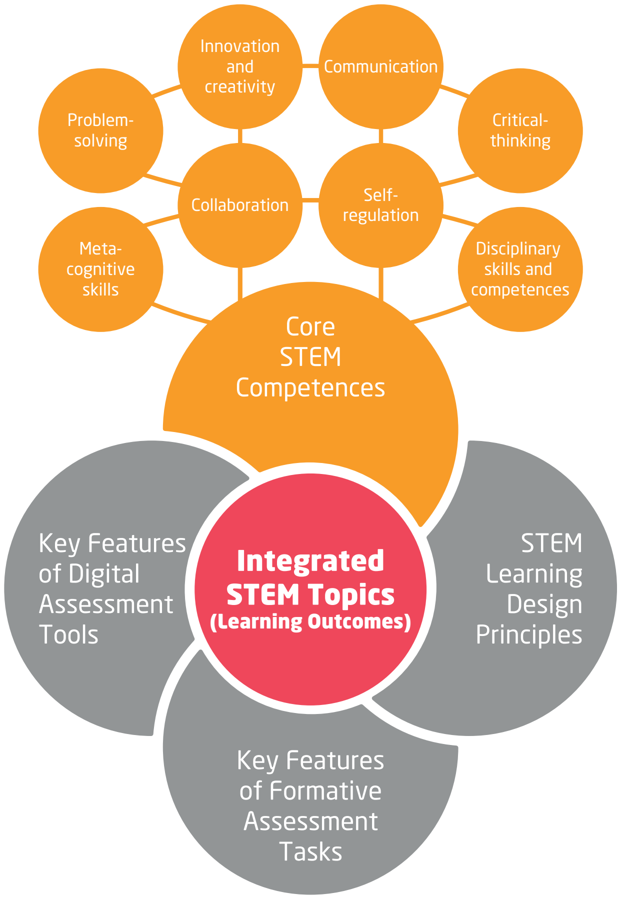


Figure 3. Core STEM Competences for Integrated STEM Education

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.

A brief overview of each of these core competences which comprise the first component of the ATS STEM Conceptual Framework is outlined below (c.f. Report #1 for further details).

Problem-solving

Problem-solving can be defined as the process of finding solutions to problems (Problem-Solving, n.d). STEM curricula should provide student experiences that include problem-solving activities which can allow students to develop STEM proficiency. 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 (European Commission, 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).

Innovation and Creativity

Students of all ages should be inspired to be innovative and entrepreneurial in their approach to generating ideas and applying them to solving problems. This is vital to help develop sustainable responses to society's most complex challenges (European Commission, 2015). STEM education has a particular role to play here since it can contribute to the development of student creativity by nurturing and inspiring their sense of curiosity (Lin & Wang, 1994).

Communication

It is undeniable that communication is not only an inevitable part of social relationships but also a significant part of success in all aspects of life including in professional contexts (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).

Critical-thinking

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). In a digital and connected world where new information is rapidly being produced the development of critical skills has never been more important.

Meta-cognitive Skills

Meta-cognition is defined as the scientific study of an individual's cognitions about his or her own cognitions. By meta-cognitive skills, Saxton et al. (2014) refer to the ability to reflect on one's own thinking and reasoning as well as choosing and strategically using tools (technological and otherwise). The development of metacognitive skills needs greater attention when one considers that metacognition and emotions play a critical role in learners' ability to monitor and regulate their learning.

Collaboration

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, Pearson & Schweingruber, 2014). Peer collaboration can help students be successful with challenging tasks and move beyond their current state of knowledge and is key to developing meta-cognitive knowledge (Honey et al., 2014). The European Commission (2019) highlights the role and importance of collaboration as a cross-cutting competency and one that can be facilitated through digital tools and networks.

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). 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, 2018).

Disciplinary Competences

Disciplinary knowledge and skills not only refers to competences from each discipline in isolation, but also combination of these disciplines. The European Commission considers STEM competency which includes knowledge, skills and attitudes of STEM disciplines as a core lifelong learning competences (European Commission, 2019). Designing learning experiences which engage students in authentic, real-world design challenges enables the development of these disciplinary knowledge and core skills across and between the combined STEM disciplines (Moore & Smith, 2014; Thibaut et al 2018c; Wang, Moore, Roehrig & Park, 2011).

STEM LEARNING DESIGN PRINCIPLES

The six characteristics of integrated STEM education combined as “STEM Learning Design Principles” are depicted in the second component of the ATS STEM Conceptual Framework in Figure 4 as follows:

- Problem Solving Design and Approaches
- Disciplinary and interdisciplinary knowledge
- Engineering design and practices
- Appropriate use and application of technology
- Use of real world contexts
- Appropriate pedagogical practices.

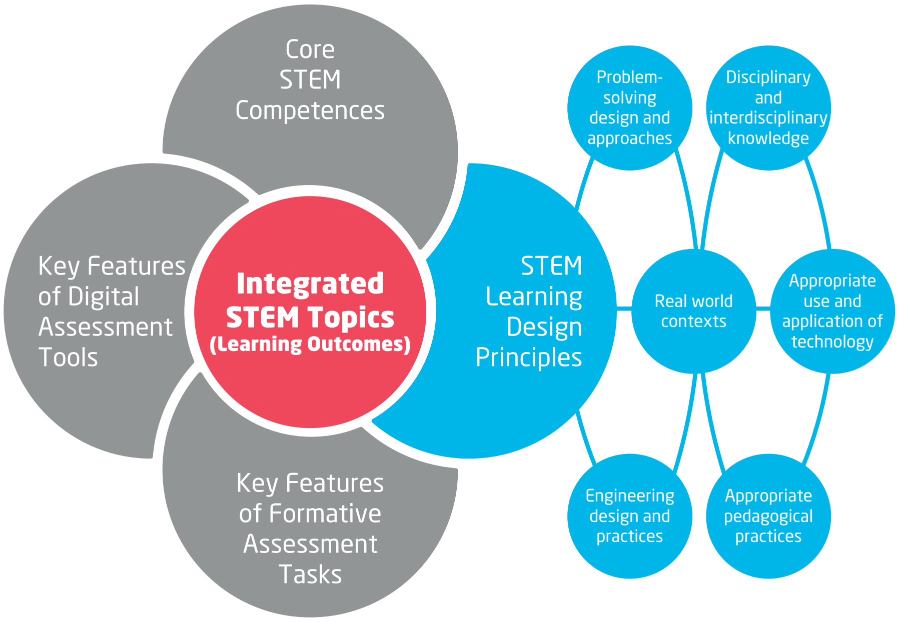


Figure 4. STEM Learning Design Principles for Integrated STEM Education

A brief overview of each of these learning design principles is outlined below (c.f. Report #1 for further details).

Problem Solving Design and Approaches
STEM curricula should provide student experiences that include problem-solving activities which can allow students to develop STEM proficiency. 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. Curriculum can be organised around problems and issues that are of personal and social significance in the real world. Problem solving design and approaches include 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).

Disciplinary and Interdisciplinary Knowledge

This principle can be considered as the backbone of STEM (Martin-Paez et al., 2019) and the complexities of these interrelationships are captured by the following statements:

- 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 artifacts, as well as the artifacts 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 necessary 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, De Loof, Boeve-de Pauw & Van Petegem, 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 or solution 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 skills both within the disciplines and across disciplines. 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. Consequently, they need support to elicit the relevant scientific or mathematical ideas in an engineering or technological design context, 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 understanding and competences to new or unfamiliar situations (Honey et al., 2014). During STEM learning, the 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 which are typically student-centred (Anderson, 2007; 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 (Thibaut et al. 2018a, Mustafa et al. 2016). When developing knowledge, engaging students in STEM activities is also significant.

Students are often disinterested in science and mathematics when they learn in an isolated and disjoined manner, missing connections to crosscutting concepts and real-world applications (Kelley & Knowles, 2016). Currently, crosscutting connections remain implicit or can be missing all together (National Research Council, 2012). These cross-cutting concepts include patterns; cause and effect; scale, proportion, and quantity; systems and system models; energy and matter; structure and function; and stability and change (National Research Council, 2012).

Making crosscutting STEM connections is complex and requires teachers to teach STEM content in deliberate ways so that students understand how STEM knowledge is applied to real-world problems (Kelley & Knowles, 2016). Crosscutting concepts provide students with connections and intellectual tools that are related across the differing areas of disciplinary content and can enrich their application of practices and their understanding of core ideas. (National Research Council, 2012, p. 233). Locating crosscutting practices will help students identify similarities in the nature of work conducted by scientists, technologists, engineers, and mathematicians and could help students to make more informed decisions about STEM career pathways (Kelley & Knowles, 2016). That is, crosscutting concepts will facilitate students' understanding of the interrelation between science, technology, engineering and mathematics.

Engineering Design and Practices

Engineering design and practices are generally neglected in the literature and therefore, needs to be promoted more (Guzey & Moore, 2015; Mohd Shahali, Halim, Rasul, Osman & Zulkifeli, 2017; Shahbazi, Jacobs, Lehnes & Mancuso, 2016; Kalaian, Kasim & Nims, 2018; Kelley & Knowles 2016). Kelley and Knowles (2016) advocated that using engineering design as a catalyst to STEM learning and overcoming the limited view of technology are 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. Lesseig, Slavit and Nelson (2017), Shahbazi et al. (2016) and Kalaian et al. (2018) provide examples of integrating engineering into STEM.

Appropriate Use and Application of Technology

Appropriate use and application of technology is an important characteristic when integrating STEM disciplines (Lesseig et al., 2017; Shaughnessy, 2013; Eguchi & Uribe,2017; Stohlmann, Moore & Roehrig, 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 and Smith (2014), Radloff and Guzey (2016) and Aydin-Gunbatar, Tarkin-Celikkiran, Kutucu and Ekiz-Kiran (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 technology 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 (Ibanez & Delgado-Kloos, 2018), developing robots (Blackley & Howell, 2019), virtual reality (O'Leary, Scully, Karakolidis, & Pitsia, 2018) and programming (Guzdial & Morrison, 2016).

Real-world Contexts

Linking STEM education to "real-world problems" is clearly audible (EL-Deghaidy, Mansour, Alzaghibi, & Alhammad,2017; Fien, 2009; Krug & Shaw, 2016; Martin-Paez et al. 2019 Yanez, Thumlert, de Castell, & Jenson, 2019). 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, mathematics and science should be brought to life through students' need to be used in order to solve a real problem (Margot & Kettler, 2019). There are many studies referring to the importance of making this connection with real world problems (e.g., Blackley & Howell, 2019; Bybee, 2013; Johnson, Peters-Burton & Moore, 2015; Kelley & Knowles, 2016; Mohd Shahali et al., 2019, Moore and Smith, 2014; Stohlmann et al., 2012), which helps make student learning more meaningful (Blackley & Howell, 2019; Turk, Kalayci & Yamak, 2018). The use of engineering design processes and finding a solution to real-world problems are key characteristics which can be utilised when developing integrated STEM activities that are highlighted in the literature (e.g. Aydin-Gunbatar et al., 2018).

Appropriate Pedagogical Practices
A range of pedagogical practices and classroom practices were advocated in the literature related to STEM programs including:

- Inquiry-based teaching method (Thibbaut et al., 2018)
- Project-based teaching method (Kennedy & Odell, 2014; Pitt, 2009; Ritz & Fan, 2015)
- STEM-based modelling activities (Davies & Gilbert, 2003; English, 2017; France, 2017; Gilbert, 2004; Hallstrom & Schonborn, 2019)
- Creating products and/or solving problems that can be made or solved using engineering principles (Blackley & Howell, 2019)
- Teaching through instructional pedagogy (Margot & Kettler, 2019)
- Teaching through the engineering design process (Kennedy & Odell, 2014)
- Teaching with grade-appropriate materials and encompassing hands-on, minds-on, and collaborative approaches to learning (Kennedy & Odell, 2014)
- Using appropriate technologies, such as modelling, simulation, and distance learning to enhance STEM education learning experiences and investigations (Kennedy & Odell, 2014)
- Using authentic learning activities (Hallstrom & Schonborn, 2019; Roth, 2012; Williams, 2011).

In particular, Margot & Kettler (2019) suggest some pedagogical practices to support STEM integration, such as:

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

KEY FEATURES OF FORMATIVE ASSESSMENT TASKS

Six key features of formative assessment tasks that were derived from the literature reviewed in this report and in Report #3 are presented in Table 3 and Figure 5.

Table 3: Key features of formative assessment tasks

Feature Number	Features of Tasks
1	Integrate STEM content (and learning outcomes/goals)
2	Reflect STEM learning design principles (and social constructivist views of learning)
3	Help to elicit evidence of learning (improve learning through questioning and discussion and by prompting activities that clarify the meaning of success - consequential validity argument 1)
4	Facilitate feedback (improve learning by prompting the learner to use effective feedback focused on the learning outcome/goal in a timely manner - consequential validity argument 2)
5	Facilitate peer-assessment (improve learning by activating students as instructional resources for one another - consequential validity argument 3)
6	Facilitate self-assessment (improve learning by activating students as owners of their own learning - consequential validity argument 4)

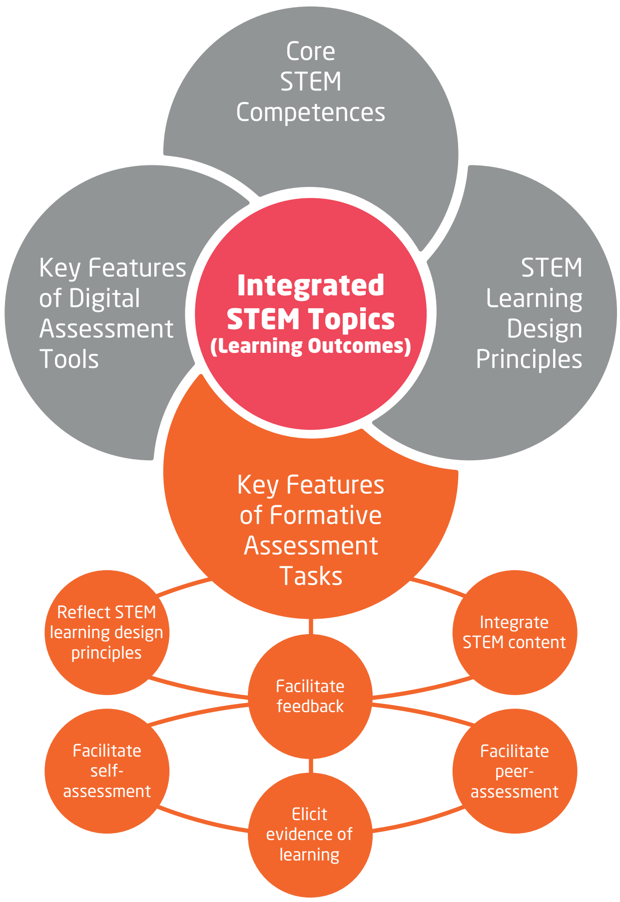


Figure 5. Key Features of Formative Assessment Tasks for Integrated STEM Education

These six key features of formative assessment tasks are now discussed under four headings: (1) underlying principles; (2) key strategies (3) the need for validity evidence; and, (4) effective feedback.

Underlying Principles

As far as it is possible, tasks developed to support formative assessment in STEM must reflect principles outlined in the previous section and discussed in Report #3. In that report it was noted that Thibbaut et al. (2018) identified five distinct but related key principles underlying instructional practices in STEM Education. The first key principle – integration of STEM content – entails purposefully integrating content from various STEM disciplines. The second key principle – problem-centred learning – supports the use of authentic real-world problems to increase the relevance of the learning content. The third principle – inquiry-based learning – allows students to discover new concepts and develop new understandings as they engage with assessment tasks. The fourth principle – design-based learning – refers to learning environments that engage students in technological or engineering design while engaged in formative assessment. The final principle – cooperative learning – involves the promotion of teamwork and collaboration with others through the use of STEM assessment tasks. It should be noted that in contrast to the instructional practice of 'collaborative learning', 'cooperative learning' emphasises teachers' guidance. In the case of collaborative learning, the teacher will not actively monitor the different student groups and will refer all substantive questions back to the group to resolve. While the first principle can be deemed essential for thinking about STEM content, principles two to five are rooted in a social constructivist view on learning, and are central to developing a coherent pedagogical approach to assessment in the area.

Key Strategies

Formative assessment is a cyclical process involving the elicitation of evidence, interpretation of evidence, and action based on that evidence (Wiliam & Black, 1996). Wiliam and Thompson (2007) propose five strategies supporting this process:

- Clarifying, sharing, and understanding learning intentions and criteria for success;
- Engineering effective classroom discussions, questions, and tasks that elicit evidence of learning;
- Providing feedback that moves learners forward;
- Activating students as instructional resources for one another; and
- Activating students as owners of their own learning.

The Need for Validity Evidence

Bennett (2011) argues that the success of any formative assessment process rests on the accurate interpretation of the evidence elicited. The standards for educational and psychological testing (American Educational Research Association et al., 2014) list many different forms of evidence that may contribute to a validity argument for an assessment. However, not all are weighed equally in formative assessment. Stobart (2006) writes: "The deceptively simple claim of this chapter is that for formative assessment to be valid it must lead to further learning. The validity argument is therefore about the consequences of assessment" (p. 133). Other forms of validity evidence (e.g., content, criterion) may play supporting roles, but if a formative assessment does not support/improve student learning, it cannot be said to be valid for its intended purpose. Thus, attention to student learning that occurs as a result of formative assessment is an essential part of the assessment's validity argument.

Given the importance of consequences for establishing validity in formative assessment, and the central role that feedback plays in formative assessment, as noted in Report #3, a consideration of what constitutes effective feedback is warranted. Wiliam (2016) notes that "the only important thing about feedback is what students do with it" (p. 10). While there is no way to guarantee that students will use feedback in a given situation, there are some forms of feedback that stand a greater chance of being effective than others.

Effective Feedback

Hattie and Timperley (2007) propose a three-part framework for situating feedback. This involves attention to articulating ultimate goals for students ("Feed Up"), giving students an indication of their progress ("Feed Back"), and showing students where they should move to the next ("Feed Forward") (p. 87). As with the formative assessment strategies discussed above, attention to the ultimate goal is essential when providing students with feedback. If feedback is not focused on advancing students' progress towards goals, and it cannot be useful to improve student learning.

Feedback can fall into one of four categories: 1) Feedback about a specific task; 2) Feedback about a process; 3) Feedback related to self-regulation; or 4) Feedback directed at the personal self. According to Hattie and Timperley (2007), feedback related to process and self-regulation is most helpful in advancing student learning. Limited task-oriented feedback may also be useful; however, feedback directed at the personal self is not helpful because it focuses on the student as a person rather than being directed towards the instructional goal (e.g., "You did a great job!").

Content is not the only feedback-related variable contributing to the use of feedback by students. Time is also essential. Cowie, Moreland, and Otrel-Cass (2013) note that classroom teachers must "plan for and organise time for both the provision of feedback and *for students to make sense of and use the feedback"* (emphasis added, p. 99). If feedback is provided to a student, but the lesson immediately moves on, there is no real opportunity for the student to learn from the feedback that was provided.

KEY FEATURES OF DIGITAL ASSESSMENT TOOLS

Interest in technology-enhanced formative assessment has grown rapidly within the past few decades (Shute & Rahimi, 2017). One of the main reasons for this is the potential of technology to either deploy or enable the provision of feedback in a timelier manner compared to a teacher unaided by technology (Spector et al., 2016). Technology-enhanced assessments also may be able to measure constructs and process previously inaccessible, rendering them potentially transformative for the science of assessment (Shute, Leighton, Jang, & Chu, 2016).

Four key features of digital assessment tools that were derived from a targeted review of relevant literature in Report #4 are introduced in Table 4 and Figure 6 and expanded upon in the following discussion.

Table 4: Key features of digital assessment tools

Feature of the tool	Explanation
Functional	It supports sending and displaying, processing and analysing in an interactive environment
Flexible	It supports the assessment of different types of learning
Practical	It requires teacher professional development but is relatively easy and cost effective to use
Useful	It helps to improve learning by facilitating timely feedback focused on learning outcomes/goals (and supports the consequential validity argument)

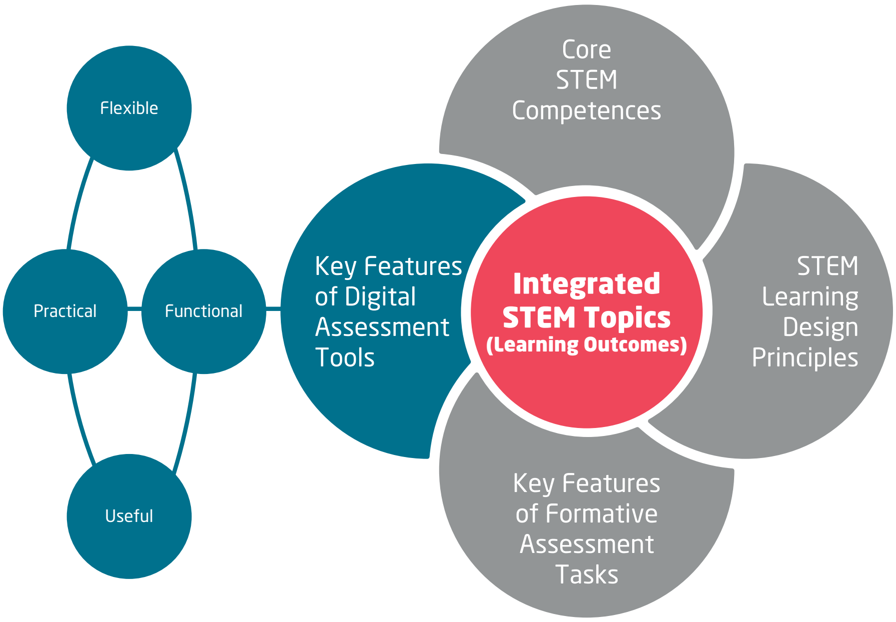


Figure 6. Key Features of Digital Assessment Tools for Integrated STEM Education

Functional
The Formative Assessment in Science and Mathematics Education (FaSMED; European Commission, 2015) framework integrates technological functions with formative assessment and includes three ways in which that can occur:

- Sending and Displaying: These are actions that facilitate communication between the different actors in the formative assessment process; they can be thought of as facilitating the elicitation and student response processes. A classroom response system where students reply to items using phones or tablets and results are displayed for the class would be an example of this.
- Processing and Analysing: These are actions where technology supports the interpretation phase of formative assessment, such as extracting or summarizing relevant data. An example of this would be a data dashboard summarizing student performance.
- Providing an Interactive Environment: These are actions that enable students to work individually or collaboratively to explore content and may include features from the other two categories. Examples of this are specialised software for allowing students to explore geometrical drawings or other specific topics.
- Each of the three technology functionalities may be useful for any of the five formative assessment strategies.

Flexible
One of the most-heralded benefits of technology-enhanced assessment is flexibility in the incorporation of new item types capable of providing more nuanced information than simple multiple-choice or constructed-response items (Sireci & Zenisky, 2006). For example, students may carry out tasks in extended and dynamic contexts – such as the problem-solving and inquiry tasks incorporated into the 2019 eTIMSS assessment (Martin, Mullis, & Foy, 2017). Problem- and inquiry-based tasks at the classroom level may also be enhanced by incorporation of technological tools, such as those developed by NASA's Classrooms for the Future initiative (Hickey, Taashoobshirazi, & Cross, 2012). Embedded within a meaningful ongoing context, such assessment items may have the potential to realize Kelley and Knowles's (2016) unified framework for STEM.

In addition to providing a meaningful context with engaging items, technology-enhanced assessment can aid inquiry in other ways. For example, incorporation of technology-enhanced assessment can automate the feedback process for students completing an inquiry-based task. A variety of different automated feedback conditions may be programmed into the assessment, allowing differentiation based on students' specific outcomes (e.g., Ryoo & Linn, 2016).

Incorporation of technology into classroom assessment practice can also enhance collaborative learning among students in a myriad of ways. Dukuzumuremyi and Siklander, (2018) report on student-to-student interaction over laptops in a Finnish primary school context. They found that students interacted verbally, nonverbally (e.g., typing notes into a shared document), and kinaesthetically (e.g., shaking hands in agreement) around the laptops while engaging in collaborative computer instruction. van Dijk and Lazonder (2016) discuss peer evaluation of inquiry-based concept maps in a technology-enhanced learning environment for middle school students. ePortfolios have also been used for collaborative formative assessment in university courses concerning design and technology. After assembling ePortfolios, students engaged in an adaptive comparative judgment task, helping them to clarify their own understandings of design quality by holistically evaluating the work of others (Canty, Seery, Hartell, & Doyle, 2017; Seery, Canty, & Phelan, 2012).

With respect to mobile learning, Nikou and Economides (2018) reviewed 43 pieces of literature related to mobile-based assessment. They found that mobile-based assessment was most commonly used among primary school students for STEM subjects and that most studies came from Taiwan, China, the United States, or Spain. They conclude that findings regarding mobile based assessment are generally positive, noting that 60% of reviewed studies found positive relationships between mobile assessment and achievement (and 33% of students did not explicitly discuss student achievement). Additionally, mobile-based assessment seemed to be perceived positively by students, although this finding was extrapolated from student comments in the studies rather than statistical analysis.

And, of course, the incorporation of technology into formative assessment may also assist with enabling access for students with disabilities.

Practical and Useful

Several studies indicate that teachers require appropriate support and professional development in order to successfully integrate digital tools into their classrooms and that that perceived benefits (e.g. positive impact on learning) and ease of use are important factors for teachers when considering digital tools.

Feldman and Capobianco (2008) examined United States teachers' processes of integrating a personal response system (PRS) for formative assessment into physics classes. The PRS included hardware and software including remotes that students use to send answers to a computer that then displays the results in a histogram" (p. 82). The system came pre-programmed with physics questions; teachers could also create their own. Eight physics teachers were interviewed three times over the course of PRS adoption; classes were also observed 3-5 times. The authors found that teachers (particularly novice teachers) struggled to manage the logistics of implementing the PRS, but teachers did grow in their use and understanding of the PRS over time. Teachers tended not to use the pre-programmed physics items because they were not well-aligned with what was being taught. Teachers also used the PRS in unexpected ways, such as polling students' attitudes about issues in science.

Lee, Feldman, and Beatty (2010) conducted a survey of primary and secondary teachers in the United States in order to capture perceptions about the challenges of incorporating classroom response systems (CRS) into formative assessment. The authors found that many factors influenced teachers' use of CRS, including logistical issues (e.g., time, difficulty operating technology), classroom or pedagogical issues (e.g., difficulty writing effective questions, lack of skill conducting formative assessment, student behaviour, difficulty facilitating whole-class discussions), and broader contextual factors (e.g., non-school commitments, teachers' beliefs about the technology).

Kimbell (2012) provides an overview of implementation for project e-scape. This digital portfolio assessment system involves students (initially in design/technology courses, later expanded to science and geography) using PDAs to create ePortfolios documenting their learning processes. Student-to-student feedback is integrated as part of the process. Kimbell (2012) notes the importance of providing appropriate training to teachers throughout the implementation process, covering topics such as the general structure of the project e-scape activities and how best to facilitate them. Other key issues that are highlighted include the manageability of integrating the system into classrooms and the pedagogical issue of "the extent to which the use (for assessment purposes) of such a system can support and enrich the learning experience of design & technology" (Kimbell, 2007, p. 21).

Panero and Aldon (2016), also part of the FaSMEd study, carried out a case study of a 9th grade mathematics class that integrated tablets into instruction for formative assessment purposes. Three classroom observations were conducted over the course of a year. During the first observation, students tended to complete their work using paper and pencil and used the tablets only for submitting answers. By the third observation, the tablets were more integrated into students' learning processes. The most common uses of the tablet system by the teacher were displaying and discussing the work of a particular student or surveying the class. Geer, White, Zeegers, Au, and Barnes (2017) conducted a mixed methods study to examine the integration of iPads into instruction in an Australian context. The authors found that students and teachers both found the iPads to be useful for giving or receiving feedback.

Nikou and Economides (2019) examined the utility of a model for capturing teachers' acceptance of mobile based assessment. The proposed technology acceptability model included ease of use, perceived utility, teacher mobile self-efficacy, social circumstances, facilitating school conditions, and perceptions of how well mobile assessment systems perform their intended functions. In all, 161 teachers from different European countries were surveyed regarding how each piece of the model related to their intention to use mobile based assessment. Results revealed that perceived ease of use and usefulness were the most important factors.

EXPANDED ATS STEM CONCEPTUAL FRAMEWORK

As indicated in the introduction, this report is the final in a series of five linked reports exploring the literature on STEM education. It outlines existing frameworks for STEM education, which in turn informed the initial development of the ATS STEM Conceptual Framework that aims to inspire the classroom practices of integrated STEM education topics and their assessment. This provisional framework also draws on key findings from the series of linked reports (Reports #1 - #4) of the ATS STEM project. Report #1 describes the findings of a literature review which particularly focuses on research and related publications perceived to adopt or reflect a more integrated understanding of STEM education in schools. A survey of European partners and analysis of related national STEM education policies forms the basis of Report #2 which also informs the thinking reflected in the ATS STEM Conceptual Framework. Finally, Report #3 and #4 address the area of assessment and more specifically examines different aspects and examples of digital formative assessment methods and tools that can be used in STEM education.

Most importantly, all of this work informed the development of the ideas, concepts, and understandings presented in this final report and visually synthesised in the expanded ATS STEM Conceptual Framework as depicted in Figure 7 that supports us achieving the objectives of the ATS STEM project. Our aim is to provide conceptual tools to help us map out this large complex problem. It should help us relate skills and competences to STEM, to assessment, to digital tools all grounded in the unique local contexts in which education is enacted. The framework will help the project partnership come to a common understanding of assessment of transversal skills in STEM and use this as a basis to build tools and inform learning designs. We aim to draw on the framework in having conversations about how we design learning experiences, about how we digitally assess students to help them learn and ultimately enable them to develop the transversal skills and competences skills to engage and interact as curious and STEM literate citizens.

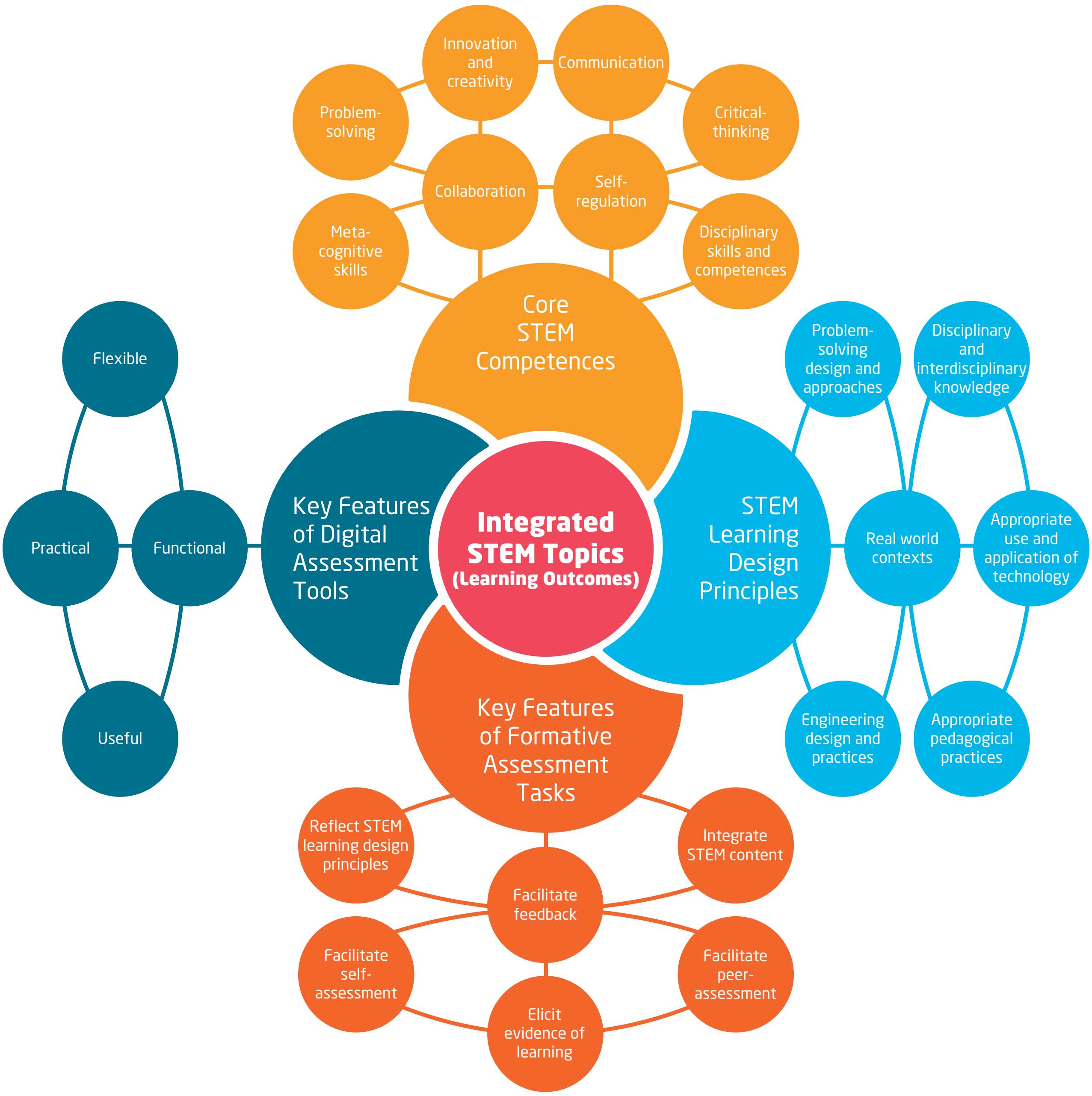


Figure 7. Expanded ATS STEM Conceptual Framework for Integrated STEM Education

REFERENCES

Ajzen, I. & Fishbein, M. (1975). Beliefs, attitudes, intention, and behavior: an introduction to theory and research. Reading, MA: Addison-Wesley.

American Educational Research Association; Joint Committee on Standards for Educational and Psychological Testing (U.S.); American Psychological Association; National Council on Measurement in Education. (2014). Standards for educational and psychological testing. Washington, DC: American Educational Research Association.

Atkinson, R. D. (2012). Why the current education reform strategy won't work. *Issues in Science and Technology, 28*(3), 29-36. https://issues.org/atkinson-7/

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. *Chemistry Education Research and Practice, 19*(3), 954-972, doi: 10.1039/C8RP00128F

Beane, J. A. (1997). Curriculum integration: Designing the core of democratic education. Teachers College Press.

Bennett, R.E. (2011). Formative assessment: A critical review. *Assessment in Education: Principles, Policy, and Practice, 18*(1), 5-25, doi: 10.1080/0950069042000323719

Blackley, S., & Howell, J. (2019). The Next Chapter in the STEM Education Narrative: Using Robotics to Support Programming and Coding. *Australian Journal of Teacher Education, 44*(4), 4, doi: 10.14221/ajte.2018v44n4.4

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

Problem-Solving (n.d.) Cambridge Business English Dictionary, Cambridge University Press, https://dictionary.cambridge.org/

Canty, D., Seery, N., Hartell, E., & Doyle, A. (2017). *Integrating peer assessment in technology education through adaptive comparative judgement*. Paper presented at Pupils' Attitudes Toward Technology (PATT-34) Conference. Philadelphia, PA. https://www.iteea.org/File.aspx?id=115739&v=21dfd7a

Carretero, S.; Vuorikari, R., & Punie, Y. (2017). DigComp 2.1: The Digital Competence Framework for Citizens with eight proficiency levels and examples of use, EUR 28558 EN, doi:10.2760/38842

Cook, M. P. (2006). Visual representations in science education: The influence of prior knowledge and cognitive load theory on instructional design principles. Science Education, 90(6), 1073-1091.

Corlu, M. S. (2013). Insights into STEM education praxis: An assessment scheme for course syllabi. *Kuram ve Uygulamada Eğitim Bilimleri, 13*(4), 2477-2485, doi: 10.12738/estp.2013.4.1903

Corlu, M. S., Capraro, R. M., & Capraro, M. M. (2014). Introducing STEM education: Implications for educating our teachers in the age of innovation. *Eğitim ve Bilim, 39*(171), 74-85. http://hdl.handle.net/11693/13203

Costello, E., Girme, P., McKnight, M. , Brown, M. & Kaya, S. (2020) Government Responses to the Challenge of STEM Education: Case Studies from Europe ATS STEM Report #2. Dublin: Dublin City University. doi: 10.5281/zenodo.3673600

Cowie, B., Moreland, J., & Otrel-Cass, K. (2013). *Expanding notions of assessment for learning inside science and technology primary classrooms.* Rotterdam, The Netherlands: Sense Publishers.

Davies, T., & Gilbert, J. (2003). Modelling: Promoting creativity while forging links between science education and design and technology education. Canadian Journal of Math, Science & Technology Education, 3(1), 67-82.

Dukuzumuremyi, S., & Siklander, P. (2018). Interactions between pupils and their teachers in collaborative and technology-enhanced learning settings in the inclusive classroom. *Teaching and Teacher Education, 76*, 165-174. doi: 10.1016/j.tate.2018.08.010

Eguchi, A., & Uribe, L. (2017). Robotics to promote stem learning: Educational robotics unit for 4th grade science. In *2017 IEEE Integrated STEM Education Conference (ISEC)* (pp. 186-194). IEEE. doi: 10.1109/ISECon.2017.7910240

EL-Deghaidy, H., Mansour, N., Alzaghibi, M., & Alhammad, K. (2017). Context of STEM Integration in Schools: Views from In-service Science Teachers. *Eurasia Journal of Mathematics, Science and Technology Education, 13*(6), 2459-2484. doi: 10.12973/eurasia.2017.01235a

ENCoRE,(2005). Commission Staff Working Document Towards A European Qualifications Framework For Lifelong Learning. http://www.encore-edu.org/ENCoRE-documents/consultation_eqf_en.pdf

English, L. D. (2017). Advancing elementary and middle school STEM education. *International Journal of Science and Mathematics Education, 15*(1), 5-24.

European Commission. (2015). Encouraging STEM Studies for the Labour Market, Luxembourg: Publications Office of the European Union https://www.europarl.europa.eu/RegData/etudes/STUD/2015/542199/IPOL_STU(2015)542199_EN.pdf

European Commission. (2016). FaSMEd summary report. https://cordis.europa.eu/docs/results/612/612337/final1-final-fasmed-summary-report-final.pdf

European Commission (2019). Key competences for lifelong learning. European reference framework. Luxembourg: Publications Office of the European Union https://op.europa.eu/en/publication-detail/-/publication/297a33c8-a1f3-11e9-9d01-01aa75ed71a1/language-en

European Schoolnet. (2018). *Science, Technology, Engineering and Mathematics Education Policies in Europe* [Scientix Observatory Report]. Brussels: European Schoolnet.

Feldman, A., & Capobianco, B.M. (2008). Teacher learning of technology enhanced formative assessment. *Journal of Science Education Technology, 17*, 82-99. doi: 10.1007/s10956-007-9084-0

Fien, J. (2009). Teaching and learning for a sustainable future. a multimedia teacher education programme. https://unesdoc.unesco.org/ark:/48223/pf0000125238

France, B. (2017). Modeling in technology education: A route to technological literacy. Handbook of Technology Education, 1–11.

Geer, R., White, B., Zeegers, Y., Au, W., & Barnes, A. (2017). Emerging pedagogies for the use of iPads in schools. *British Journal of Educational Technology, 48(*2), 490-498. doi: 10.1111/bjet.12381

Gilbert. (2004). Models and modelling: ROUTES to more authentic science education. 2(2), 115–130.

Griffin P., Care E. (2015) The ATC21S Method. In: Griffin P., Care E. (eds) Assessment and Teaching of 21st Century Skills. Educational Assessment in an Information Age. Springer, Dordrecht

Guzdial, M., & Morrison, B. (2016). Growing computer science education into a STEM education discipline. *Communications of the ACM, 59*(11), 31–33. doi: 10.1145/3000612

Guzey, S. S., & Moore, T. J. (2015). Assessment of Curricular Materials for Integrated STEM Education (RTP, Strand 4). In *2015 ASEE Annual Conference & Exposition* 26.260. http://www.asee.org/file_server/papers/attachment/file/0005/4185/ASEE_AssessingCurric_GuzeyandMoore.pdf

Guzey, S. S., Moore, T. J., & Harwell, M. (2016). Building up STEM: An analysis of teacher-developed engineering design-based STEM integration curricular materials. *Journal of Pre-College Engineering Education Research (J-PEER), 6*(1), 11-29. doi: 10.7771/2157-9288.1129

Hallström, J., & Schönborn, K. J. (2019). Models and modelling for authentic STEM education: Reinforcing the argument. *International Journal of STEM Education, 6(*1), 22. doi: 10.1186/s40594-019-0178-z

Hattie, J., & Timperley, H. (2007). The power of feedback. *Review of Educational Research, 77*(1), 81-112. doi: 10.3102/003465430298487

Hickey, D.T., Taasoobshirazi, G., & Cross, D. (2012). Assessment as learning: enhancing discourse, understanding, and achievement in innovative science curricula. *Journal of Research in Science Teaching, 49*(10), 1240-1270. doi: 10.1002/tea.21056

Honey, M., Pearson, G., & Schweingruber, H. (Eds.). (2014). *STEM integration in K-12 education: Status, prospects, and an agenda for research* (Vol. 500). Washington, DC: National Academies Press. https://www.nap.edu/read/18612

Hudson, P., English, L., Dawes, L., King, D., & Baker, S. (2015). Exploring links between pedagogical knowledge practices and student outcomes in STEM education for primary schools. *Australian Journal of Teacher Education (Online), 40*(6), 134. doi: 10.14221/ajte.2015v40n6.8

Houston J. (2007) Future Skill Demands, from a Corporate Consultant Perspective; Presentation at the Workshop on Research Evidence Related to Future Skill Demands, National Research Council.

Ibáñez, M.-B., & Delgado-Kloos, C. (2018). Augmented reality for STEM learning: A systematic review. *Computers & Education, 123*, 109–123. doi: 10.1016/j.compedu.2018.05.002

Johnson C.C. (2013) Conceptualizing integrated STEM education. School Science and Mathematics, 113(8) 367–368.

Johnson, C. C., Peters-Burton, E. E., & Moore, T. J. (Eds.). (2015). *STEM road map: A framework for integrated STEM education.* Routledge.

Kalaian, S., Kasim, R., & Nims, J. (2018). Effectiveness of Small-Group Learning Pedagogies in Engineering and Technology Education: A Meta-Analysis. *Journal of Technology Education, 29*(2), 20–35. doi: 10.21061/jte.v29i2.a.2

Kelley, T. R., & Knowles, J. G. (2016). A conceptual framework for integrated STEM education. *International Journal of STEM Education, 3*(1), 11. doi: 10.1186/s40594-016-0046-z

Kennedy, T. J., & Odell, M. R. L. (2014). Engaging Students in STEM Education. *Science Education International, 25(*3), 246–258.

Kimbell, R. Wheeler, T. Miller, S. and Pollitt A. (2007). E-scape portfolio assessment – the final report of project e-scape (phase 2). Technology Education Research Unit. Goldsmiths University of London.

Kimbell, R. (2012). Evolving project e-scape for national assessment. *Int J Technol Des Educ, 22,* 135–155. doi: 10.1007/s10798-011-9190-4

Krug D. & Shaw A. (2016) Reconceptualizing ST®E(A)M(S) Education for Teacher Education, Canadian Journal of Science, Mathematics and Technology Education, 16(2). 183-200, https://doi.org/10.1080/14926156.2016.1166295

Kurup, P. M., Li, X., Powell, G., & Brown, M. (2019). Building future primary teachers' capacity in STEM: Based on a platform of beliefs, understandings and intentions. *International Journal of STEM Education, 6*(1), 10. doi: 10.1186/s40594-019-0164-5

Lee, H., Feldman, A., & Beatty, I.D. (2012). Factors that affect science and mathematics teachers' initial implementation of technology-enhanced formative assessment using a classroom response system. Journal of Science Education Technology, 21, 523-539.

Lesseig, K., Slavit, D., & Nelson, T. H. (2017). Jumping on the STEM bandwagon: How middle grades students and teachers can benefit from STEM experiences. *Middle School Journal, 48*(3), 15–24. doi: 10.1080/00940771.2017.1297663

Lin, H. & Wang, M-J. (1994) Creativity Assessment Packet. Tapei: Psychological Publishing Co.

Margot, K. C., & Kettler, T. (2019). Teachers' perception of STEM integration and education: A systematic literature review. *International Journal of STEM Education, 6*(1), 2. doi: 10.1186/s40594-018-0151-2

Marope, M., Griffin, P., & Gallagher, C. (2017). *Future competences and the future of the curriculum.* Geneva: International Bureau of Education/UNESCO. (http://www.ibe.unesco.org/sites/default/files/resources/future_competences_and_the_future_of_curriculum.pdf)

Martin, M. O., Mullis, I. V. S., & Foy, P. (2017). *TIMSS 2019 Assessment Design.* In I. V. S. Mullis & M. O. Martin (Eds.), TIMSS 2019 Assessment Frameworks (pp. 79-91). http://timss2019.org/wp-content/uploads/frameworks/T19-Assessment-Frameworks-Chapter-4.pdf

Martín-Páez, 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. *Science Education, 103*(4), pp.799-822. doi:10.1002/sce.2152.

Mayer, R. E., Bove, W., Bryman, A., Mars, R., & Tapangco, L. (1996). When less is more: Meaningful learning from visual and verbal summaries of science textbook lessons. *Journal of Educational Psychology, 88*(1), 64–73. doi:10.1037/0022-0663.88.1.64

McGuinness, C. (2018). Informed Analysis of 21st Century Competencies in a Redeveloped Primary Curriculum. Final Report. https://ncca.ie/media/4307/research-informed-analysis-of-21st-century-competencies-in-a-redevloped-curriculum.pdf

McLoughlin, E., Butler, D. Kaya, S. & Costello, E. (2020). STEM Education in Schools: What can we Learn from the Research? *Report #1 In ATS STEM Report Series.* Dublin: Dublin City University. http://dx.doi.org/10.5281/zenodo.3673728

McNeill, K.L. and Krajcik, J. (2012). Supporting grade 5-8 students in constructing explanations in science: The claim, evidence, and reasoning framework for talk and writing. Boston: Pearson

Mohd Shahali, E. H., Halim, L., Rasul, M. S., Osman, K., & Mohamad Arsad, N. (2019). Students' interest towards STEM: a longitudinal study. *Research in Science & Technological Education, 37*(1), 71-89. doi: 10.1080/02635143.2018.1489789

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. *EURASIA Journal of Mathematics, Science and Technology Education, 13*(5), 1189–1211. doi: 10.12973/eurasia.2017.00667a

Moore K. A., & Smith, T. J. (2014). Advancing the state of the art of STEM integration. *Journal of STEM Education, 15*(1), 5-10. https://pdfs.semanticscholar.org/312c/5379e2c93fd4317053d27bb7181a935909f5.pdf

Mustafa, N., Ismail, Z., Tasir, Z., Said, M., & Haruzuan, M. N. (2016). A meta-analysis on effective strategies for integrated STEM education. *Advanced Science Letters, 22*(12), 4225-4228. doi: 10.1166/asl.2016.8111

Nathan, M., & Pearson, G. (2014, June). Integration in K–12 STEM education: Status, prospects, and an agenda for research. In *2014 ASEE Annual Conference & Exposition* 24-781. http://nap.edu/18612

National Governors Association. (2007). Building a science, technology, engineering and math agenda. https://files.eric.ed.gov/fulltext/ED532528.pdf.

National Research Council. 2012. A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas. Washington, DC: The National Academies Press. doi: 10.17226/13165

Nikou, S.A., & Economides, A.A. (2018). Mobile-based assessment: A literature review of publications in major referred journals from 2009 to 2018. *Computers & Education, 125*, 101-119. doi: 10.1016/j.compedu.2018.06.006

Nistor, A., Gras-Velazquez, A., Billon, N., & Mihai, G. (2018). *Science, Technology, Engineering and Mathematics Education Practices in Europe* [Scientix Observatory Report]. Brussels: European Schoolnet. http://www.scientix.eu/observatory

OECD, DeSeco. (2005). Definition and Selection of Key Competencies-Executive Summary. http://www. deseco. admin. ch/bfs/deseco/en/index/02. html.

OECD (2018). The future of education and skills 2030: The future we want. Paris: OECD. (http://www.oecd.org/education/2030/oecd-education-2030-position-paper.pdf) http://www.oecd.org/education/school/Flyer-The-Future-of-Education-and-Skills-Education-2030.pdf.

O'Leary, M., Scully, D., Karakolidis, A., & Pitsia, V. (2018). The state-of-the-art in digital technology-based assessment. *European Journal of Education, 53*(2), 160–175. doi: 10.1111/ejed.12271.

Panero, M., & Aldon, G. (2016). How teachers evolve their formative assessment practices when digital tools are involved in the classroom. Digital Experiences in Mathematics Education, 2, 70-86.

Peeck, J. (1993). Increasing picture effects in learning from illustrated text. Learning and Instruction, 3(3), 227–238.

Pitt, J. (2009). Blurring the boundaries–STEM education and education for sustainable development. Design and Technology Education: An International Journal, 14(1). https://ojs.lboro.ac.uk/DATE/article/view/201.

Radloff, J., & Guzey, S. (2016). Investigating Preservice STEM Teacher Conceptions of STEM Education. *Journal of Science Education and Technology, 25*(5), 759–774. doi: 10.1007/s10956-016-9633-5

Reynolds, K., O'Leary, M., Brown, M. & Costello, E. (2020) Digital Formative Assessment of Transversal Skills in STEM: A Review of Underlying Principles and Best Practice. ATS STEM Report #3. Dublin: Dublin City University. https://doi.org/10.5281/zenodo.3666584

Redecker, C. (2017). European framework for the digital competence of educators: DigCompEdu (No. JRC107466). Joint Research Centre (Seville site). http://publications.jrc.ec.europa.eu/repository/bitstream/JRC107466/pdf_digcomedu_a4_final.pdf

Panero, M., & Aldon, G. (2016). How teachers evolve their formative assessment practices when digital tools are involved in the classroom. *Digital Experiences in Mathematics Education, 2*, 70-86. doi: 10.1007/s40751-016-0012-x

Ritz, J. M., & Fan, S.-C. (2015). STEM and technology education: International state-of-the-art. *International Journal of Technology and Design Education, 25*(4), 429–451. doi: 10.1007/s10798-014-9290-z

Roth, W.-M. (2012). Authentic school science: Knowing and learning in open-inquiry science laboratories (Vol. 1). Springer Science & Business Media.

Rychen, D.S., & Salganik, L.H. (Eds.). (2003). Key competencies for a successful life and a well-functioning society. Gottingen, Germany: Hogrefe & Huber.

Ryoo, K., & Linn, M.C. (2016). Designing automated guidance for concept diagrams in inquiry instruction. *Journal of Research in Science Teaching, 53*(7), 1003-1035. doi: 10.1002/tea.21321

Sanders, M. (2009). Integrative STEM education: Primer. The Technology Teacher, 68(4), 20–26.

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. *Studies in Educational Evaluation, 40*, 18–35. doi: 10.1016/j.stueduc.2013.11.005

Seery, N., Canty, D., & Phelan, P. (2012). The validity and value of peer assessment using adaptive comparative judgement in design driven practical education. *International Journal of Technology Design Education, 22*, 205-226.

Shahbazi, Z., Jacobs, M., Lehnes, A., & Mancuso, K. (2016, August). Designing Integrated STEM Education: Linking STEM Teachers and Learners in a K-20 Continuum. In *ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. V003T04A022-V003T04A022. American Society of Mechanical Engineers.

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

Shute, V.J., & Rahimi, S. (2017). Review of computer-based assessment for learning in elementary and secondary education. *Journal of Computer Assisted Learning, 33*, 1-19. doi: 10.1111/jcal.12172

Shute, V.J., Leighton, J.P., Jang, E.E., & Chu, M. (2016). Advances in the Science of Assessment. *Educational Assessment, 21*(1), 34-59. doi: 10.1080/10627197.2015.1127752

Sireci, S.G., & Zenisky, A.L. (2006). Innovative item formats in computer-based testing: In pursuit of improved construct representation. In Downing, S.M. & Haladyna, T.M. (Eds.). *Handbook of test development* (329-348). New York, NY: Routledge.

Smith, L., & Southerland, S. (2007). Reforming practice or modifying reforms? Elementary teachers' response to the tools of reform. *Journal of Research in Science Teaching, 44*(3), 396–423. https://doi: 10.1002/tea.20165

Spector, J.M., Ifenthaler, D., Sampson, D., Yang, L., Mukama, E., Warusavitarana, A., Dona, K.L., Eichorn, K., Fluck, A., Huang, R., Bridges, S., Lu, J., Ren, Y., Gui, X., Deenan, C.C., San Diego, J., & Gibson, D.C. (2016). Technology enhanced formative assessment for 21st century learning. *Educational Technology and Society, 19*(3), 58-71.

Stobart, G. (2006). The validity of formative assessment. In Garder, J. (Ed.). *Assessment and Learning*. Thousand Oaks, CA: SAGE Publications Ltd.

Stohlmann, M., Moore, T. J., & Roehrig, G. H. (2012). Considerations for teaching integrated STEM education. *Journal of Pre-College Engineering Education Research (J-PEER), 2*(1), 4. doi: 10.5703/1288284314653

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? *International Journal of Science Education, 41*(10), 1387-1407. doi: 10.1080/09500693.2019.1607983

Szendey, O. O'Leary, M. (M. Scully, C., Brown, M. & Costello, E. 2020). Virtual Learning Environments and Digital Tools for Implementing Formative Assessment of Transversal Skills in STEM. *Report #4 In ATS STEM Report Series.* Dublin: Dublin City University. http://doi: 10.5281/zenodo.367478

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., & Depaepe, F. (2018). Integrated STEM education: A systematic review of instructional practices in secondary education. *European Journal of STEM Education, 3*(1), 2. doi: 10.20897/ejsteme/85525

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

Thibaut, L., Knipprath, H., Dehaene, W., & Depaepe, F. (2018b). How school context and personal factors relate to teachers' attitudes toward teaching integrated STEM. *International Journal of Technology and Design Education, 28*(3), 631-651. doi: 10.1007/s10798-017-9416-1

Thibaut, L., Knipprath, H., Dehaene, W., & Depaepe, F. (2018c). Teachers' attitudes toward teaching integrated stem: The impact of personal background characteristics and school context. *International Journal of Science and Mathematics Education, 17*(5), 987-1007. doi: 10.1007/s10763-018-9898-7

Thomas, B., & Watters, J. J. (2015). Perspectives on Australian, Indian and Malaysian approaches to STEM education. *International Journal of Educational Development, 45*, 42–53. doi: 10.1016/j.ijedudev.2015.08.002

Turk, N., Kalayci, N., & Yamak, H. (2018). New trends in higher education in the globalizing world: STEM in teacher education. *Universal Journal of Educational Research, 6*(6), 1286-1304. doi: 10.13189/ujer.2018.060620

van Dijk, A.M., & Lazonder, A. (2018). Scaffolding students' use of learner-generated content in a technology-enhanced inquiry learning environment. *Interactive Learning Environments, 24*(1), 194-204. doi: 10.1080/10494820.2013.834828

Wang, H. H., Moore, T. J., Roehrig, G. H., & Park, M. S. (2011). STEM integration: Teacher perceptions and practice. *Journal of Pre-College Engineering Education Research (J-PEER), 1*(2), 2. doi: 10.5703/1288284314636

Wiliam, D. (2016). The secret of effective feedback. *Educational Leadership, 73*(7), 10-15. http://www.ascd.org/publications/educational-leadership/apr16/vol73/num07/abstract.aspx#The_Secret_of_Effective_Feedback

Wiliam, D., & Black, P. (1996). Meanings and consequences: A basis for distinguishing formative and summative functions of assessment? *British Educational Research Journal, 22*(5), 537-548. doi: 10.1080/0141192960220502

Wiliam, C., & Thompson, M. (2007). Integrating assessment with learning: What will it take to make it work? In C.A. Dwyer (Ed.). *The future of assessment: Shaping teaching and learning*. New York, NY: Lawrence Erlbaum Associates.

Williams, J. (2011). STEM education: Proceed with caution. Design and Technology Education: An International Journal, 16(1). https://jil.lboro.ac.uk/ojs/DATE/article/view/1590

Wong, G. K., & Huen, J. H. (2017). A conceptual model of integrated STEM education in K-12. In *2017 IEEE 6th International Conference on Teaching, Assessment, and Learning for Engineering (TALE)* (pp. 296-302). IEEE.

Yanez, G. A., Thumlert, K., de Castell, S., & Jenson, J. (2019). Pathways to sustainable futures: A "production pedagogy" model for STEM education. *Futures, 108*, 27-36. doi: 10.1016/j.futures.2019.02.021

APPENDIX A

Assessment of Transversal Skills in STEM (ATS STEM)
Erasmus+ Call reference: EACEA/28/2017

Terms of Reference for Work Package 1, Task 1- 4 and Work Package 2, Tasks 1-2

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 Core 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.

WP 2 – STEM Formative Digital Assessment Approach
Work package (WP2) is focused on digital assessment and provides an evidence-based platform for the formative assessment of STEM learning tasks. It will result in a carefully selected STEM formative assessment digital tool package that fits the development and assessment of transversal skills as agreed upon in WP1. The outcomes of the comparison or adaptability of tools for STEM formative assessment will raise awareness of the didactic implications of formative assessment in the teaching and learning process. The development and/or adaptation of a tool package will be carried out basing on careful review of existing solutions and in close cooperation with key users in order to suit the needs of the piloting partner's schools and support the didactic purpose of the chosen assessment as well as suit considerations regarding storage of evidence and quality assurance of the assessment operation and outcome.

Task 1: Formative Assessment Design: Building Critical Skills in STEM: How Digital Assessment Can Give Learners Feedback
The initial task will involve:

- A review and synthesis of the research literature on STEM formative digital assessment with particular respect to schools.
- A mapping of the current state of the art of STEM formative digital assessment to show the state of the art in this area. It will highlight how students can best be scaffolded towards the development of Core STEM skills and how digital tools can capture the evidence for this and augment teaching practices to help provide constructive feedback on student progress.

Output: A review and synthesis of state of the art on STEM formative digital assessment with particular respect to schools.

Task 2: Architectural Implementation of the tool platform for Formative Assessment of Core STEM Skills
This task will involve the design of an architecture using the digital tool identified for formative assessment concentrated on how that tool may be adapted for assessment of STEM transversal skills. This adaptation will involve the development or repurposing of the identified tool to suit local contexts and cultural conditions. It will highlight the key potential affordances for leaners of the tool.

Output: Architectural design and implementation of tool adapted for assessment of STEM transversal skills that demonstrates the key potential affordances for leaners of the tool.

APPENDIX B

Characteristics of STEM Education Frameworks

Core STEM Competences

This section outlines several other STEM conceptual frameworks. The figures shown are adapted from the figures in the original sources.

A conceptual framework was developed by Kurup et al. (2019) to improve teachers' capacity, particularly their skills and competences, to deal with STEM in their future teaching, and is presented in Figure 8. While Tier 1 is representing the platform generation structure (theoretical part of the platform), Tier 2 represents the capacity building of teachers (practical part of the platform).

Tier 1.		
Beliefs	Understandings	Intentions
Based on Theory of Reasoned Action (Ajzen & Fishbein, 1980) generated Beliefs, Understandings and Intentions to teach STEM and finding their interrelationship		

Lead

Tier 2.	
Based on confidence, competence and skills in teaching STEM at present	Suggestions of requirements for future engagement with STEM

Figure 8: Conceptual framework of future primary teachers' platform of capacity to deal with STEM in their future teaching (Kurup et al., 2019, p.5)

Disciplinary and Interdisciplinary Knowledge

No framework was found in the integrated STEM education literature specifically targeting disciplinary and interdisciplinary knowledge. However, many frameworks referred to pedagogical knowledge. For example, Hudson et al. (2015) developed a framework targeting pedagogical knowledge practices (See Figure 9).

Figure 9: Pedagogical knowledge practice framework (Hudson et al. 2015, p.136)

In Figure 9, the interconnectivity of the 11 pedagogical knowledge practices is presented, and content knowledge is mentioned as one of them. Hudson et al. (2015) provided the following five examples to better explain these practices:

a. Planning teaching strategies can assist with classroom management or preparation and can include preparing for assessment to address students' learning needs.

b. A teacher can plan and timetable a STEM activity with consideration of the preparation requirements, including resources for engaging in the activity and specific teaching strategies that may assist students to learn the content knowledge.

c. The teacher may be required to solve problems for engagement in the activity with pre-emptive thinking and making adjustments during the teaching and learning experience.

d. The teacher's questioning throughout the activity is used to guide individuals and groups, together with a clear implementation structure such as an informative introduction that engages students followed by hands-on activities, that can be used as assessment and reveal student learning outcomes.

e. Teachers have individual viewpoints about how to enact the aforementioned practices such as how to plan, prepare, manage the classroom and assess students. These individual viewpoints vary from teacher to teacher with the understanding that teachers have different views on teaching any given lesson.

This model can be utilised during the process of planning teacher education/professional development programmes.

Problem-solving

One framework referring to problem solving was the Claim-Evidence-Reasoning (CER) framework initially developed by McNeill & Krajcik (2012) for constructing scientific explanations. Lesseig et al. (2017) utilised this framework to support argumentation in the classroom. The structure of CER for science and mathematics is presented in Table 5.

Table 5: CER framework for science explanations (McNeill & Krajick, 2012) and parallel mathematics argumentation structure (Lesseig, K., Slavit, D. & Holmlund Nelson, T., 2017, p.19)

CER for Science	CER for Mathematics
Claim – Statement or conclusion that answers the original question or problem.	Claim – Statement that expresses the answer to the question.
Evidence – Scientific data that supports the claim. Scientific data comes from observations in natural setting or controlled experiments, measurements, or valid scientific sources.	Evidence – Information that supports the claim. May include calculations or procedures used to solve the problem as well as mathematical definitions and theorems that demonstrate why the claim is true.
Reasoning - A justification that connects the evidence to the claim using scientific principles.	Reasoning – The justification that links the evidence to the claim using previously developed mathematical knowledge. Mathematical reasoning includes clear statements as to how and why previously accepted mathematical facts apply in the situation and lead naturally to the conclusion.

The CER framework (McNeill & Krajick, 2012) was introduced to establish a common language for teachers to support argumentation practices across mathematics, science, and language arts. Participants used this framework to increase argumentation in their classrooms by providing appropriate scaffolding and feedback. This common language supported collaboration across disciplines as teachers created and reflected on STEM-based curricula and instruction. In the classroom, it allowed the teachers to support students' abilities to justify their own ideas and conclusions. When students hear the same language and engage in similar processes in different disciplinary contexts, they are better able to employ the practice of argumentation and make interdisciplinary connections (Lesseig et al., 2017).

Engineering Design and Practices

Kelley & Knowles (2016) proposed a conceptual framework represented in a pulley system (See Figure 10), where situated learning, engineering design, scientific inquiry, technological literacy, and mathematical thinking are linked to each other as an integrated system. Each pulley in the system connects common practices within the four STEM disciplines and is bound by the rope of community of practice. Kelley & Knowles (2016) believe that rather than hoping students themselves will see the connections of STEM content and skills to real-life application, an integrated approach seeks to locate connections between STEM subjects and provide a relevant context for learning the content.

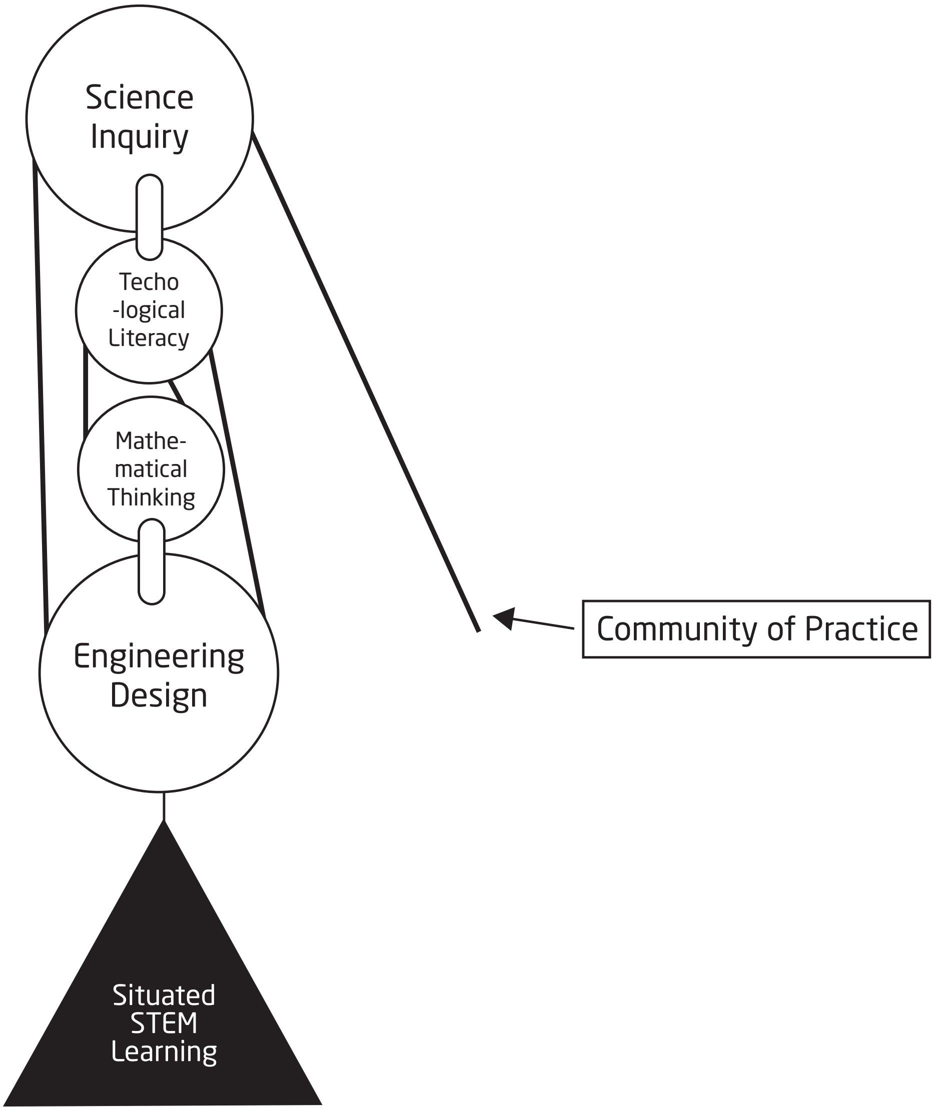


Figure 10: Graphic of conceptual framework for STEM learning (Kelley & Knowles 2016, p.4)

As illustrated in Figure 10, engineering is represented as engineering design, which is utilised in many models (e.g. Guzey, Moore & Harwell, 2016; Mohd Shahali, et al. 2017; Shahbazi et al., 2016; Kalaian et al., 2018; Kelley & Knowles 2016). For example, Lesseig et al. (2017) used the engineering design process and visualised a model for STEM integration (Figure 11) to support the enactment of challenging curriculum to enable both teachers and students to engage in all aspects of problem solving.

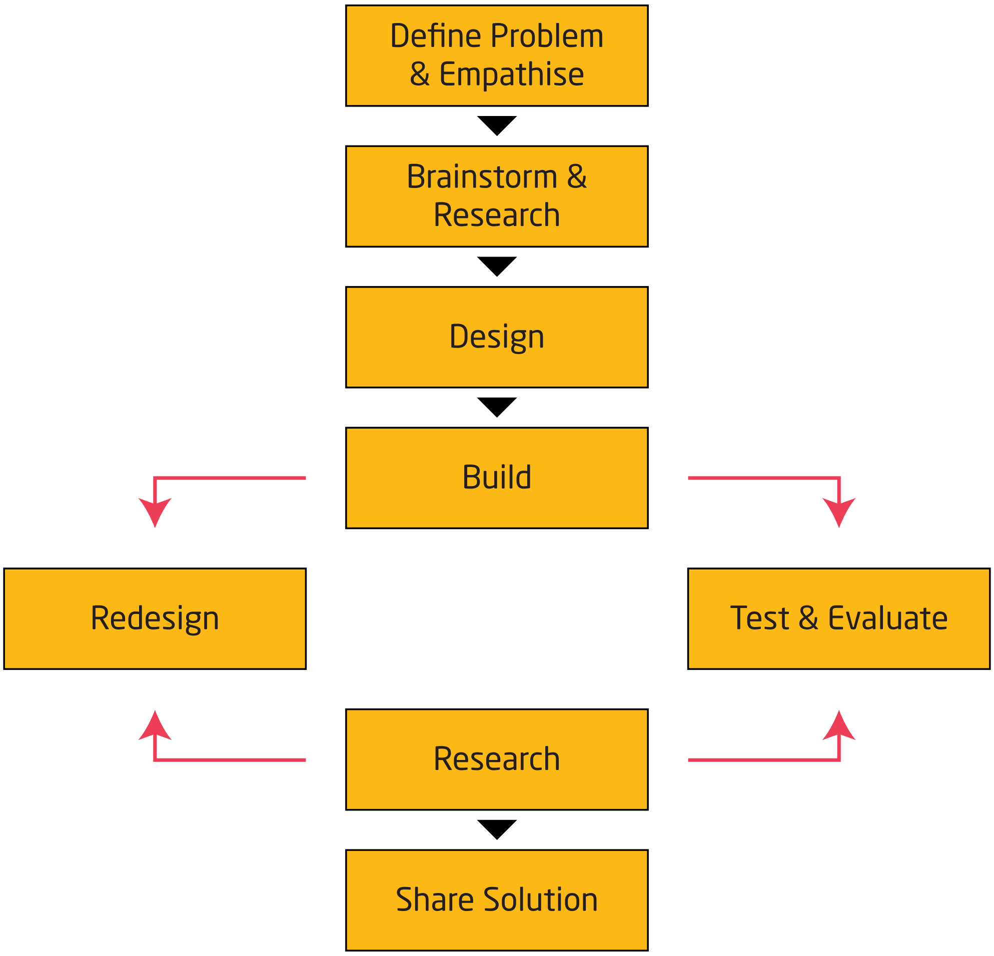


Figure 11: Engineering design process used in Teachers Exploring STEM Integration (TESI) Project (Lesseig, K., Slavit, D. & Holmlund Nelson, T., 2017, p.18)

The steps followed during the engineering design process are explained as follows:

1. Groups define the problem, which requires understanding the needs of the "client" and all of the task constraints.
2. Groups brainstorm potential solutions or solution methods and select an initial design.
3. Groups go through iterative cycles of building, testing and evaluating, and researching, which often leads to redesign. During the test and evaluate step(s), the task constraints are continually revisited to make sure that all the conditions have been met and that the solution adequately addresses the problem.
4. The final step in the process involves some form of public sharing of solutions and solution methods.

Appropriate Use and Application of Technology

Blackley & Howell (2019) conducted research to (i) unpack key elements of the Australian Curriculum: Technologies in order to support teachers and pre-service teachers to implement the curriculum and (ii) describe ways in which teachers can facilitate authentic integrated STEM education that also provides opportunities for students to develop and demonstrate 21st century competences. In their study, WeDo robotics were deployed over four weeks, for one 90-minute session per week per class. The session for each 4-week cycle positioned the students in modelling, exploring, challenging and evaluating engagements with the robots, and concurrently the level of teacher support decreased from highly-scaffolded to independent problem-solving group work. Based on the results, Figure 12 was developed.

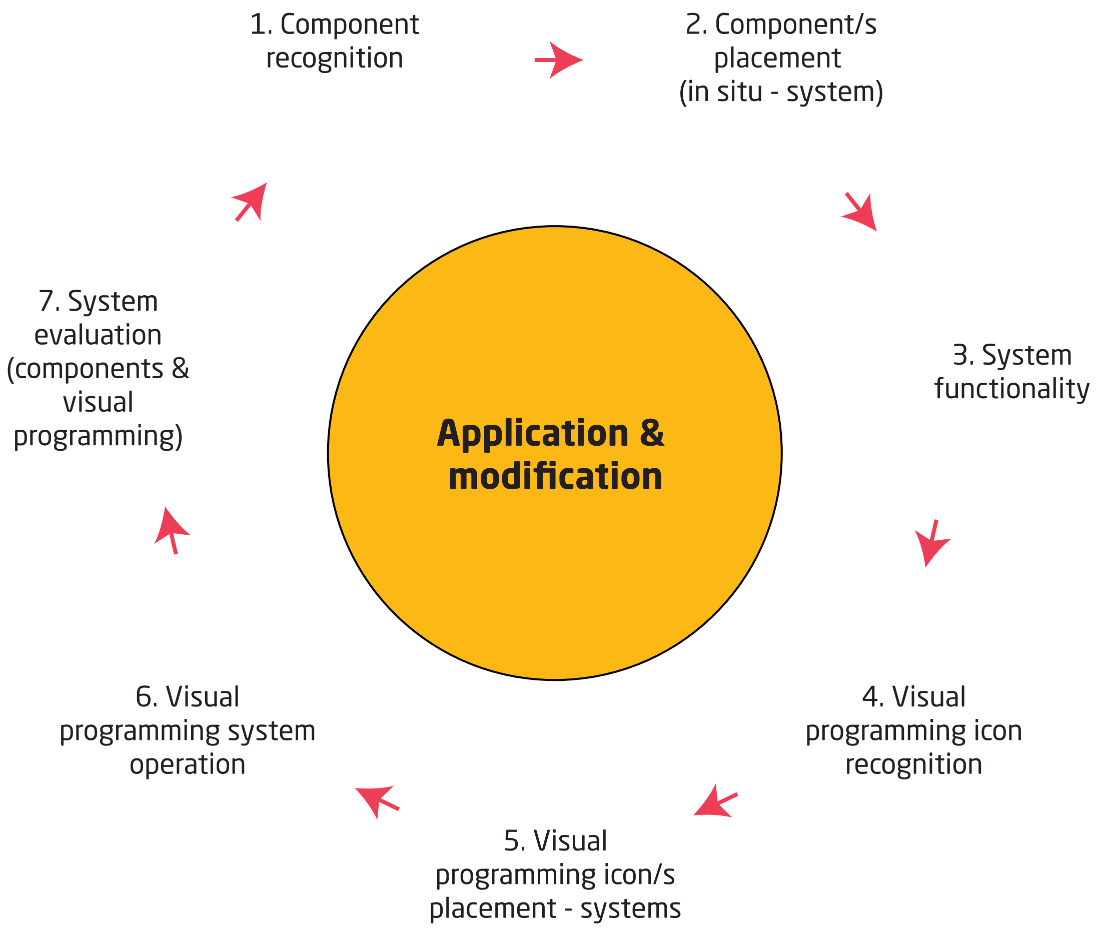


Figure 12: Framework for integrated STEM development (Blackley & Howell, 2019, p.59)

Figure 12 illustrates the stages that students were observed to have worked through during each 4-week cycle: the component related stages (1, 2, & 3), the programming related stages (4, 5, & 6), and a final evaluation of the entire system in stage 7. This framework could assist teachers in planning for integrated STEM activities.

Real-world Contexts

Integrative learning and curriculum integration theories advocate connecting subject knowledge to real-life to make it more meaningful to students through curriculum integration (Beane, 1997). There are many studies referring to the importance of making this connection with real world problems (e.g. Blackley & Howell, 2019; Bybee, 2013; Mohd Shahali et al., 2019; Johnson et al., 2015; Kelley & Knowles, 2016; Stohlmann et al., 2012), which helps make student learning more meaningful (Blackley & Howell, 2019; Turk et al. 2018). For example, Mohd Shahali et al. (2017) developed a conceptual framework to represent integrated STEM education with a special focus on the engineering design process as a bridge to connect STEM subjects together (See Figure 13). Mohd Shahali et al. (2017) represented the real-world context at the heart of integrated STEM education. The application of STEM content knowledge during the engineering design processes was viewed as the key component of students' learning in solving engineering-based problems. Mohd Shahali et al. (2017) supported that the context of instruction requires solving a real-world problem or task through teamwork.

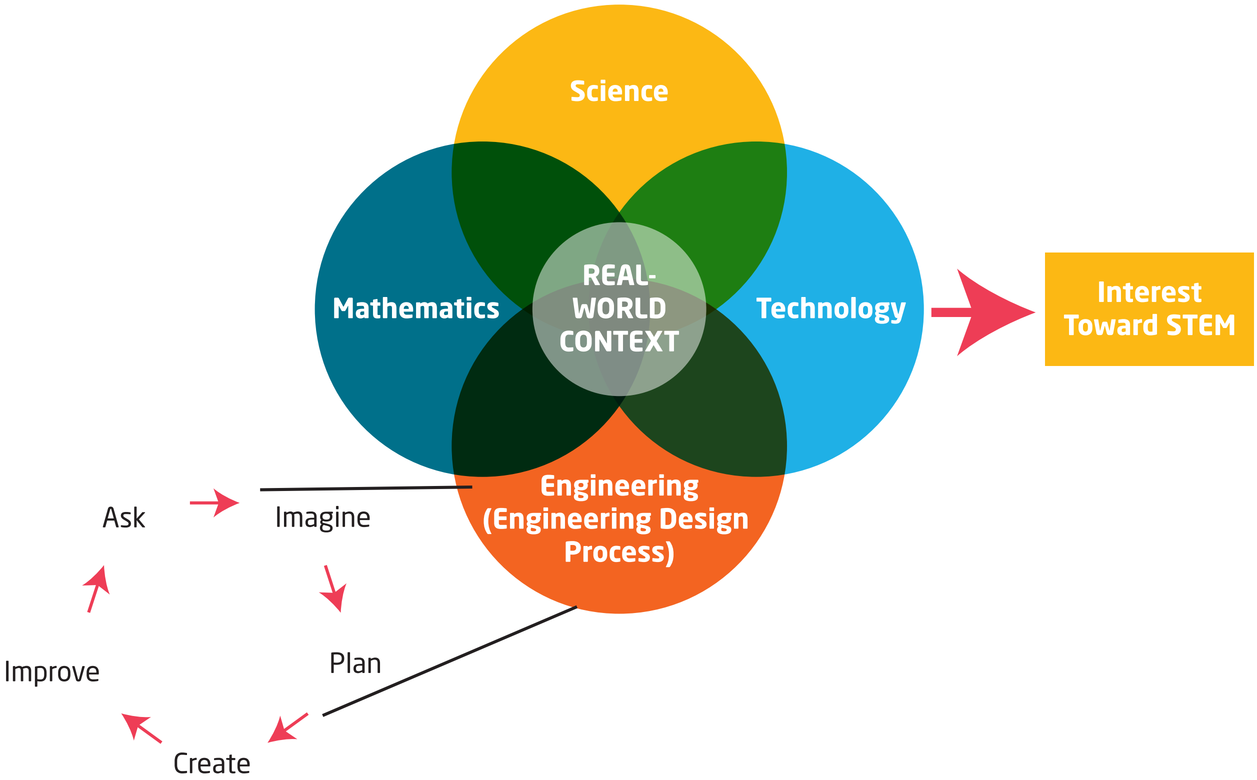


Figure 13: Conceptual framework of Bitara-STEM: Science of Smart Communities (Mohd Shahali et al. 2017, p.1195)

Based on Lesseig et al.'s (2017) study, the application of engineering design process was represented in Figure 13 with an iterative cycle of five elements; (1) ask, (2) imagine, (3) create, (4) test, and (5) improve.

Appropriate Pedagogical Practices
Thibbaut et al. (2018), based on their systematic review, developed a theoretical framework for instructional practices in integrated STEM for secondary education (Figure 14).

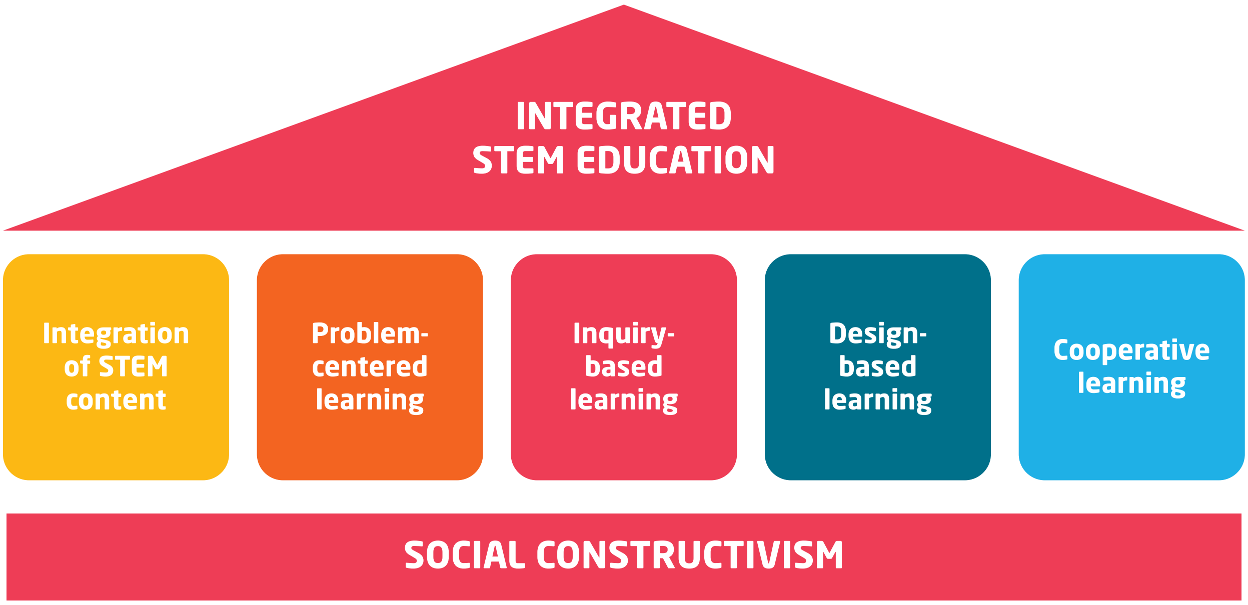


Figure 14: Theoretical framework for instructional practices in integrated STEM (Thibaut et al. 2018, p.8)

These distinctive but related five key principles are:

1. *Integration of STEM content:* entails purposefully integrating content from various STEM disciplines.
2. *Problem-centred learning:* indicates the use of authentic real-world problems to increase the relevance of the learning content.
3. *Inquiry-based learning:* allows students to discover new concepts and develop new understandings.
4. *Design-based learning:* refers to learning environments that engage students in technological or engineering design.
5. *Cooperative learning:* involves the promotion of teamwork and collaboration with others through the use of, for example, small learning groups.

In contrast to the instructional practice of 'collaborative learning', 'cooperative learning' emphasises teachers' guidance (Thibaut et al., 2018). In the latter, the teacher moves from one student-group to the other, observes and intervenes when necessary. In the case of collaborative learning, the teacher will not actively monitor the different student groups and will refer all substantive questions back to the group to resolve (Thibaut et al., 2018). These key principles were deemed most essential for teaching integrated STEM. All the principles are rooted in a social constructivist view on learning. Struyf et al. (2019) also utilised this framework.

Another framework related to appropriate pedagogical practices was developed by Wong & Huen (2017) for lesson plan and development (See Figure 15). This conceptual framework integrates knowledge from various curricula to solve real-world problems. They aimed to help students recognise and identify the various ways that subject content taught by differing curricula work together to form our world. This framework consists of five steps following each other as a cyclic process. These five steps were (1) knowledge and skills, (2) situated learning, (3) planning, (4) implementation, and (5) consolidate and question. Wong & Huen (2017) stated that this conceptual model of the STEM process is created based on scientific inquiry and engineering design.

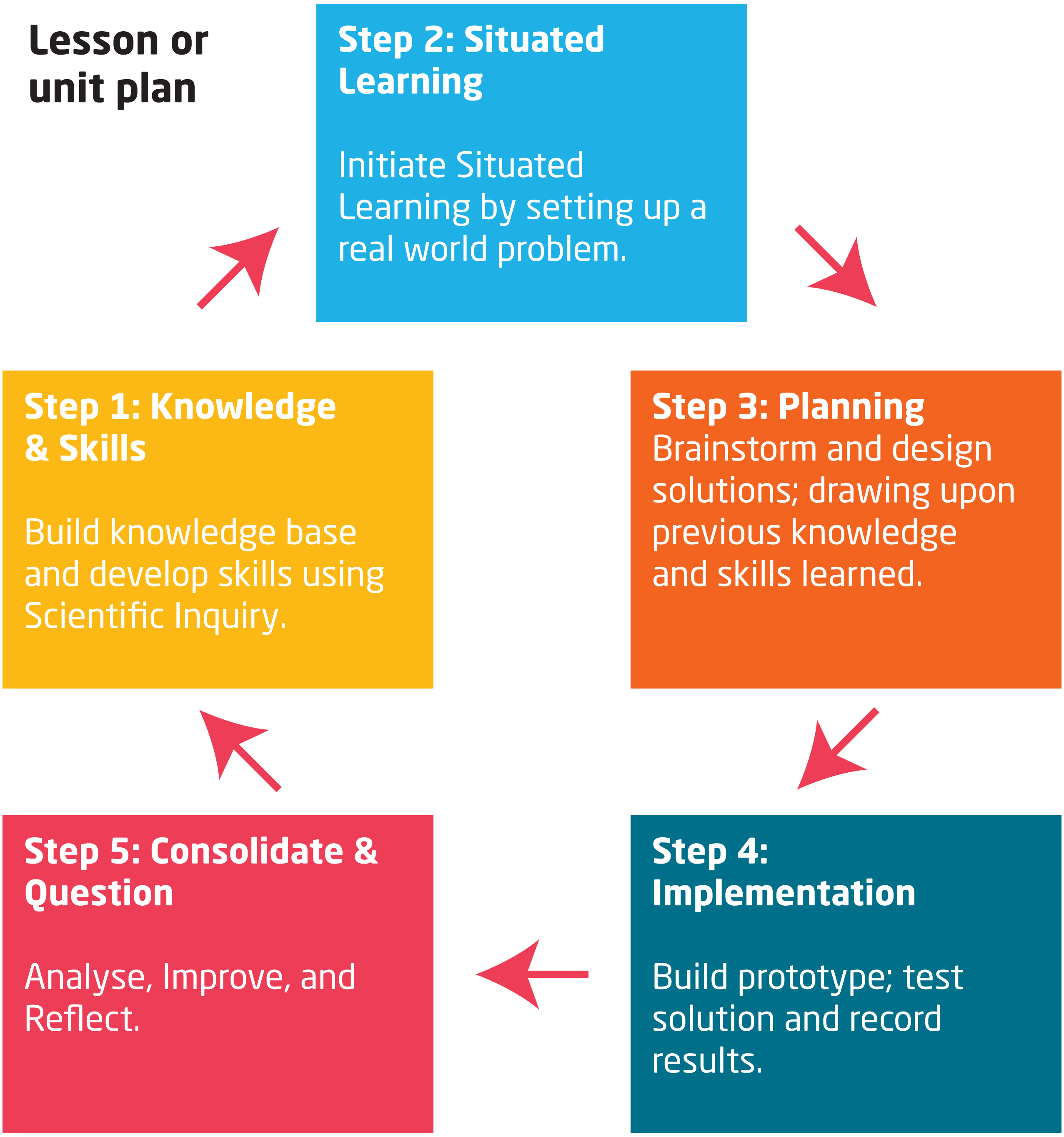


Figure 15: Conceptual model for lesson plan and development (Wong & Huen 2017, p.298)

Another framework developed by Honey et al. (2014) presents the features and subcomponents of integrated STEM education (See Figure 16). This descriptive framework refers to four main features: (i) goals of integrated STEM education, (ii) outcomes of integrated STEM education, (iii) the nature and scope of integrated STEM education, and (iv) implementation of integrated STEM education. Each feature has specific sub components (e.g. goals for students and goals for educators are the subcomponents of goals of integrated STEM education). Through the specific subcomponents presented in Figure 16, this framework provides a vocabulary for researchers, practitioners, and others to identify, describe, and investigate specific integrated STEM initiatives in the US K-12 education system.

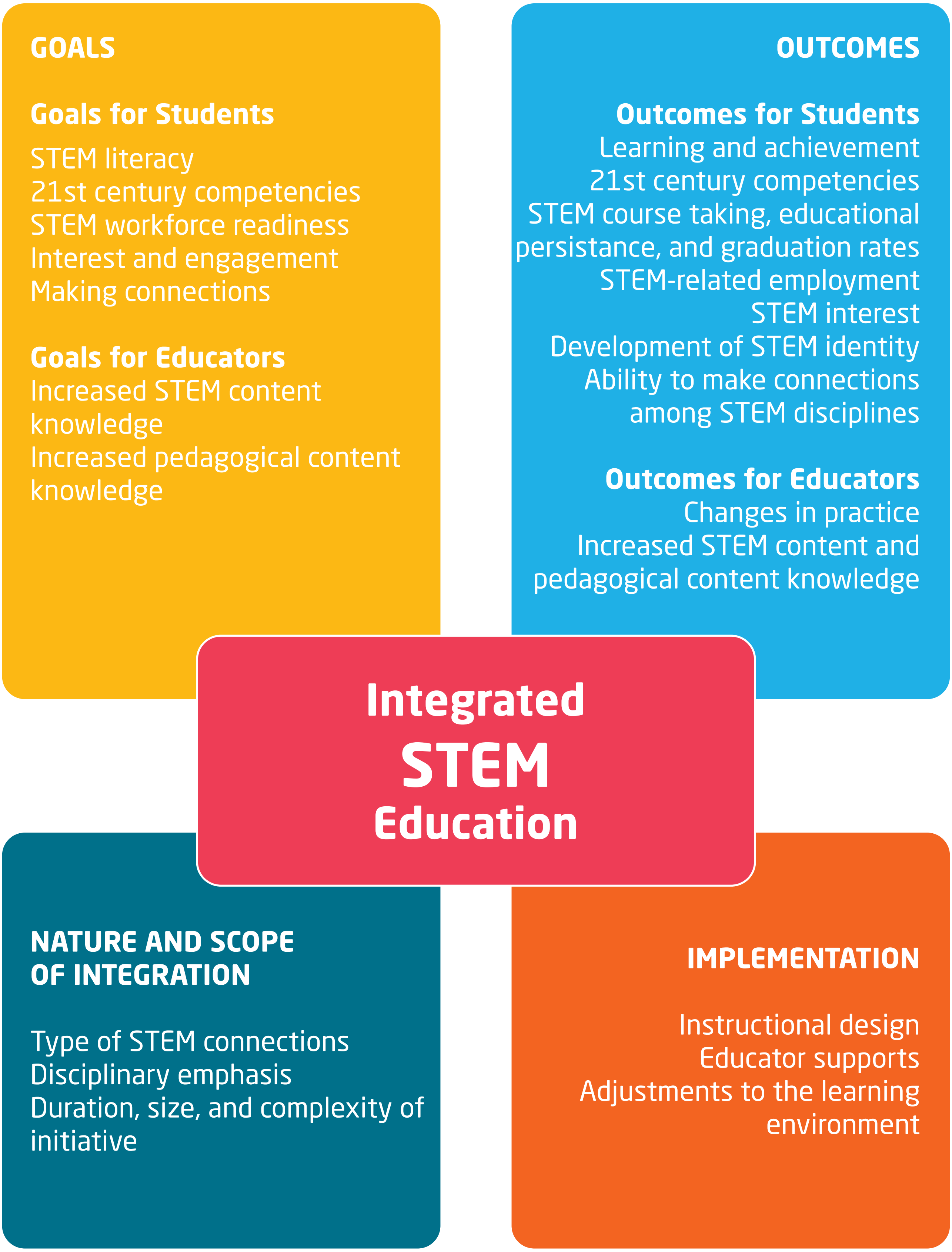


Figure 16: Descriptive framework showing general features and subcomponents of integrated STEM Education (Honey et al. 2014, p.32)

NOTES

NOTES