Assessment of STEM Competences – Systematic Overview of Model Solution and Practices

Nadezhda Kaloyanova, Prof. Dr Assen Zlatarov University, Bulgaria

The Paris Conference on Education 2023
Official Conference Proceedings

Abstract
A wide contextual understanding of STEM competence poses a strong challenge to the process of measuring and evaluating students' achievement in STEM. The problem with the assessment of STEM competences arises both from the authors' ambiguous understanding of the structure and content of STEM competence and from the variety of STEM practices in which goals are set to achieve different levels and aspects of STEM competences.The aim of this study is the main approaches for assessing STEM competences to be systematise. The research methodology is based on a systematic theoretical analysis and synthesis of three main sources of information on the research topic: official institutional sites that describe policies and tools for introducing STEM learning; publications in specialised scientific literature; practical models for introducing STEM into educational practice. The main criteria for analyzing the levels and characteristics of the integrated STEM competences and the methods and tools for their assessment. The used research methods are quantitative and qualitative content analysis, analysis of the main factors, comparative analysis. The study is a prerequisite for establishing the achievements and deficits in the assessment of STEM competences with a view to deriving a conceptual framework of an adaptive metric system for measuring and evaluating STEM competences.

Keywords: STEM Competences, Assessment, STEM Practices

Introduction

The problem of assessing the achievements of students in STEM is of key importance, since systematically assessment and monitoring of STEM guarantees the quality of STEM education. At the same time, it is considered to be one of the most critical problems due to the limitation of measurement tools and evaluation methodologies (Saxton et al., 2014).

There are two reasons for the actuality of this problem. The first reason is the complex nature of STEM competencies, which are defined as a generalized construct with many diverse components, differentiated into two main groups: knowledge, attitudes and values related to STEM-disciplines and the skills to apply acquired knowledge in accordance with ethical attitudes and values, so as to act in an appropriate, effective way in a given context (Ng, Soo Boon, 2019).

The second reason is related to the specificity of each STEM practice, which focuses on developing certain skills within different variants of STEM competence.

In this regard, for STEM education, the key issue is the types of assessment, the assessment criteria and the methods and tools with which to realize the different types of assessment, so as to cover all levels of the formed STEM competences.

With the increasingly introduction of the so-called "integrated STEM education," the opinion is imposed that formative assessment is leading for STEM, because formative assessment is a key tenant of quality STEM/technology education, as it acknowledges student progress (Peterson & Hipple, 2020). The points of view towards the criteria, methods and type of formative assessment in STEM are also not unambiguous and fit less and less into the traditional understanding of this type of assessment.

For example, Jimenez Iglesias, M. at all., described that assessment as a key element of STEM school must includes two main criteria:

- Continuous assessment – assessment typology where students are examined continuously
- Personalised assessment – assessment typology framed to demonstrate whether pupils have met specific educational goals, according to their personal development. (Jimenez Iglesias, M. at all., 2018)

Kreamer & Zimmermann introduced the concept of competency-based assessments or CBA, which entered into the STEM approach as assessments that expand students' knowledge, provide flexibility and applicability of knowledge, as well as an opportunity for the student to demonstrate learning according to his own progress, so that the maximum level of his achievement can be highlighted (Kreamer & Zimmermann, 2015).

The tendency to apply the so-called authentic assessment is confirmed, but it also proves quite difficult for teachers (McNair, Bhargava, Adams, Edgerton, & Kypros, 2003). Authentic assessment is a model of formative assessment that takes into account the social dynamics of the classroom, allows students to self-assess by determining their progress, identifying their mistakes and taking action to improve. Assessments in this type of assessment should be specific and targeted, not to cause comparison between students, but to motivate them (Peterson & Hipple, 2020; Reynolds et. al., 2020, Jimenez Iglesias, et al., 2018).

Because of the very wide range of criteria it has to cover, the formative assessment enables the flexible use of various atypical methods and tools for measuring and evaluating student achievement, such as notbooks (engineering, science), rubrics, portfolios, performance monitoring, etc. (Peterson & Hipple, 2020). Traditional methods such as standardized tests, questionnaires and practical tasks also retain their influence in formative assessment of STEM competences (Xiaoyi Gao et al., 2020. Kuen-Yi et al., 2015).

Although many opportunities it provides, the formative assessment in STEM is not enough to prove the effectiveness of STEM education. On the one hand, this type of assessment can "miss out"important key competencies that almost every STEM practice needs to develop.

Haesen et al. remark that in the analysis of studies in the field of STEM "… could not identify studies which treated the assessment of STEAM competences within learners, such as co-operation, critical thinking and creativity" (Haesen et al., 2018).

On the other hand, the main goals of STEM education is, by increasing the interest and motivation of students, to achieve higher levels of their achievements in the fields of mathematics, sciences, technology and engineering, as well as to be the basis for future career development in these fields (Kelley et al., 2016), i.e. to take into account the level of achieved academic competences through STEM teaching and learning.

In this aspect exatly, Arcin et al. emphasise one of the leading problems in STEM education research, namely the lack of common interdisciplinary frameworks for assessment. According to them, this is why many studies use large-scale assessments or test scores as indicators of STEM achievement. However, these assessment tools were not designed to measure students' STEM-related achievement (Arcin et al., 2020).

As a confirmation of this thesis, some of the countries have accepted as the leading criterion for the successful implementation of STEM education the average results achieved by students in evaluation with internationally recognised instruments. Just as often, the same countries report that students achieve unsatisfactory results, and in conditions of similar STEM education, there is a significant difference in average of achievements between students' groups in different regions or countries.

For example, in a report presenting a comparative analysis of the achievements in STEM education of 7 schools from five European countries (Belgium, UK, Italy, Portugal and Spain) it is noted that the performance of students in the PISA (OECD's Programme for International Student Assessment) and TIMSS (Trends in International Mathematics and Science Studies) tests is not good. In addition, there is considerable variation between student achievement across countries. Over 20% of students from Italy and Portugal show very low results (Haesen et al., 2018).

This trend is not unique to Europe. Simmilary, dData from the performance of students from the Gulf Cooperation Council (GCC) States on the PISA and TIMSS in the period 2011 - 2019 shows that "all six countries rank under the center point score of 500, closer to low international benchmark of 400." There is also a significant difference in the performance of students from different countries, such as students from the UAE and Bahrain appear to be the top performers among the GCC countries and KSA and Kuwait the lowest" (Kayan-Fadlelmula et al., 2022).

As a response to the identified challenges to the assessment of STEM competencies, Kaloyanova and Papancheva developed "A taxonomic framework for development of adaptive metric system for assessment of STEM-competencies" (Kaloyanova & Papancheva, 2023). The Framework includes 6 main categories of competences each with 2 subcategories:

1. Academic STEM competences
   1.1. Structured (integrated) knowledge – integrative cognitive constructs involving knowledge from the fields of mathematics, physics, chemistry, biology, engineering and technology.
   1.2. Ampliative skills – skills in the field of mathematics, physics, chemistry, biology, engineering, and technology that are amplified through the use of integrative cognitive constructs
2. Key STEM competences
   2.1. Relational competences – complex of constructive, digital and technological skills, expanding the amplibative ones.
   2.2. Extended abstract competences – analysis, synthesis and ratiocination. Building systems of key skills for research, planning and decision-making in learning situations. Inclusion of knowledge and skills in modes of divergent thinking (algorithmic, critical, strategic).
3. Transversal competences
   3.1. Problem Solving – solving authentic problems with multiple methods and techniques, incl. in a new, non-standard context.
   3.2. Innovation and creativity – Higher divergent / lateral thinking. Approbation of solutions, search for alternatives, construction of hypotheses, insight, and creativity.
4. Metacognitive competences
   4.1. Independent learning – applying strategies for emotional-social learning, argumentation and debating, curiosity and independence, learning to change.
   4.2. Self-Regulation – reflection of experience, regulation and self-regulation of learning, independent finding of solutions and answers to dilemma questions and problems.
5. Personal competences
   5.1. Motivation – demonstration of motivation, interests and sustainable attitudes towards learning and development in the field of STEM.
   5.2. Interaction – manifestations of teamwork, leadership, tolerance, communication, dealing with conflicts in real situations, learning through interaction with others.
6. STEM culture
   6.1. Cultural awareness – use of netiquette, tools for Internet security and safety in the context of global and uncontrolled communication.
   6.2. Cultural behavior – identifying/changing one's feelings, interests, values in a STEM context.

The metric system developed on the basis of the framework will contain a developed and tested metrics that can be adapted by teachers to different STEM practices and serve both for formative and summative assessment.

In order to provide an objective view of the reliability of the framework and the future development of the metric system, the aim of this study is the main approaches for assessing STEM competences to be systematize.

Methodology

The research was conducted in two stages.

In the first stage, a systematic content analysis of frameworks and systems for the assessment of STEM-competencies was carried out. A database containing scientific publications (paper and online) and publications on institutional sites has been compiled. The search was conducted using four keywords: STEM competence, assessment, system/framework and reduced to publications in the last 10 years. 2 types of frameworks and systems for assessing STEM competencies have been identified:

- Frameworks and systems for assessment of STEM educational in educational institucions - these frameworks include criteria and indicators for assessment the organisation, content, teaching and achevement in STEM;
- Frameworks and systems (or individual parts of them) for assessment students STEM-competences – these frameworks consist of criteria for assessing the STEM-competences achieved by students in STEM education.

For the purposes of this study, the frameworks and systems of the second type were analysed, with the main criterion being the assessed competences they include. A comparative analysis between the content of the analyzed frameworks and a taxonomic framework for development of adaptive metric system for assessment of STEM-competences was made. The result serves to determine specific indicators for the evaluation of STEM practices.

In the second part of the study, 88 STEM practices published in scientific papers are analyzed. The sources used are Journal of STEM in Bulgaria, Europe and the Word (all issues between 2020 and 2022 year) and Proceedings of I. and II. National conferences “STEM education and Innovations”. The analysed practices are implemented in Bulgarian school system. The practices are selected from among 232 descriptions. Selection criteria is the availability of criteria, methods and tools used for formative assessment of students.

The content analysis is implemented in three steps:

1. The type of implemented practices is defined according to two indicators:
    - The educational stage and degree in which they were implemented;
    - The pedagogical forms through which they are realized.
2. STEM-competencies that teachers assess within each practice are defined. The categories and subcategories of a taxonomic framework for development of adaptive metric system for assessment of STEM-competencies (Kaloyanova & Papancheva, 2023) were used as criteria, adding criteria for academic competencies in the field of STEM sciences.
3. The methods and tools for formative assessment applied by the teachers within the practices are presented.

The limitations of the study are related to the problems described in the theoretical analysis, as well as supplemented by the following objective factors:

- The difference in policies for the introduction of STEM in educational systems, including the broad borders for the introduction of STEM in the Bulgarian education system;
- The multitude of sources that describe research conducted on topic of this study and which are difficult to cover;

- The probability that good STEM practices in the field of formative assessment are not published, resp. are available for analysis;
- The too narrow scientific scope of some studies – for example, with a focus on a certain educational stage, assessment method, assessment criteria, type of assessment i.e.

Results

The results of the comparative analysis between the systematized frameworks and systems for assessment of students STEM competencies and a taxonomic framework for development of adaptive metric system for assessment of STEM-competencies are shown in Table 1.

Table 1: Comparative Analyse between Frameworks and Systems to Assessment of school students STEM competences

FRAMEWORKS	COMPETENCES ASSESSED	Relevance to Taxonomic Framework	TYPE OF ASSESSMENT
STEM Common Measurement System (Students Learning Construct) ***Saxon et al., 2013***	• Academic Identity • Motivational Resilience • Higher-Order Cognitive Skills • Application of Conceptual Knowledge	• Cultural behavior • Motivation • Ampliative Skills • Structured Knowledge	Formative
The FaSMEd framework ***European Commission, 2016, p. 5-6***	**Sending and Displaying:** These are actions that facilitate communication between the different actors in the formative assessment process. **Processing and Analyzing:** These are actions where technology supports the interpretation phase of formative assessment. **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.	• Interaction • Relational competences	Formative
Integrated STEM Assessment Model ***Bicer et all., 2017***	Integrative knowledge and skills from the field of science and mathematics	• Structured Knowledge • Ampliative Skills	Summative
Adaptive formative assessment platform for STEM Education ***Avgerinos, 2017***	Knowledge and Skills from the field of mathematic in primary and secondary education	Non	Formative

A spiders' web framework for STEAM education ***Haesen & Van de Put, 2018***	• Creativity • Communication • Ecology • Critical Thinking • Problem Solving	• Innovation and Creativity • Interaction • Structured Knowledge • Ampliative Skills • Extended abstract competences • Problem Solving	Formative
STEM Competences Assessment Framework ***Arican et all., 2020***	Integrative knowledge and skills from the field of science and mathematics • Mathematics - Algorithmic thinking - Concepts and principles - Pattern recognition - Argumentation • Science - Scientific literacy: Physics - Scientific literacy: Chemistry - Scientific literacy: Biology • Technology and engineering - Modeling - Technology and engineering problems - Coding	• Structured Knowledge • Ampliative Skills	Summative
Assessment of Transversal Skills (ATS STEM Model) ***Szendey, O. Et all, 2020***	• Problem Solving, Metacognitive Skills, Collaboration, Innovation and Creativity • Communication, Self-Regulation, Critical Thinking, Disciplinary Skills competences	• Problem Solving • Metacognitive competences • Innovation and Creativity • Interaction • Extended abstract competences • Structured Knowledge • Self-Regulation	Formative
Equity-Oriented Conceptual Framework for K-12 STEM literacy ***Jackson et al., 2021***	• Critical thinking and problem-solving • Empathy • STEM dispositions – attitude toward, interest in, and motivation in STEM • Utility and Applicability • Stem Identity Development • Empowerment – ability to taking responsibility, self-control, self-development	• Extended abstract competences • Problem Solving • Interaction • Cultural behavior • Motivation • Self-Regulation • Independent learning • Cultural awareness	Formative

8 frameworks developed in the last 10 years are derived from various sources. 6 of them (75%) are for formative assessment and two (25%) – for summative (Table 1).

In the comparative analysis with a taxonomic framework for the development of an adaptive metric system for the assessment of STEM competencies, the following results are obtained:

- Structured (integrated) knowledge – 5 (62,5%);
- Ampliative skills – 4 (50%);
- Interaction – 4 (50%);
- Extended abstract competences – 3 (37,5%);
- Problem Solving – 3 (37,5%);
- Innovation and creativity – 2 (25%);
- Self-Regulation – 2 (25%);
- Motivation – 2 (25%);
- Metacognitive competences – 1 (12,5%);
- Independent learning – 1 (12,5%);
- Relational competences – 1 (12,5%);
- Cultural awareness – 1 (12,5%);
- Cultural behavior – 1 (12,5%).

The greatest comparability between the systematised frameworks/systems and the taxonomic framework is based on the criteria for assessment of Structured (integrated) knowledge, Ampliative skills and Interaction – more than 50% of the systematized franeworks/sistems contain this criterion.

The least relevance is observed for the criteria Metacognitive competences, Independent learning, Relational competences, Cultural awareness, and Cultural behavior – they are presented on average in one framework/system. There is no framework or system that covers all the criteria of a taxonomic framework.

In the second part of the study, 88 school STEM practices described by teachers are analysed. Figure 1 shows the distribution of practices according to the stage and degree in which they are implemented, as well as according to the forms to which they are implemented (Figure 1).

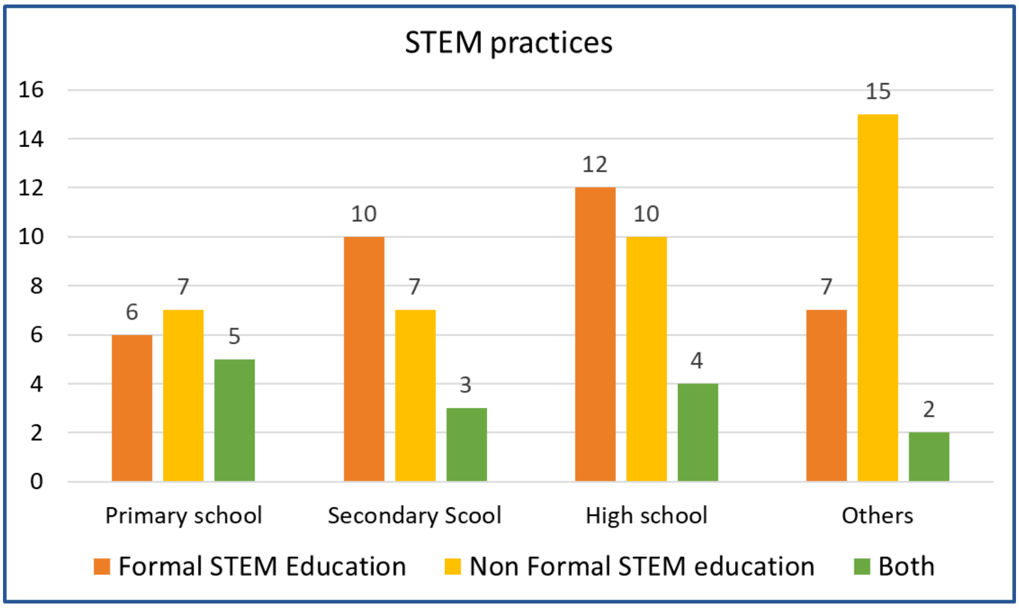

Figure 1: Type of STEM practices in %.

18 practices are implemented in the primary school stage, 20 in the middle school stage, 16 in the high school stage, and 24 practices are implemented in mixed groups with students of different degrees and ages (Figure 1).

35 STEM practices are implemented within the formal educational process – such as STEM lessons and learning projects. 39 are realised in the form of extracurricular and free time activities, and 14 covered activities both in the formal and informal educational process (Figure 1).

Through content analysis, the types of STEM competencies that teachers assess within each practice have been determined. The categories and subcategories of a taxonomic framework for development of adaptive metric system for assessment of STEM-competencies (Kaloyanova & Papancheva, 2023) are used as criteria, criteria for academic competencies in the field of STEM sciences are added. The distribution is shown in Figure 2.

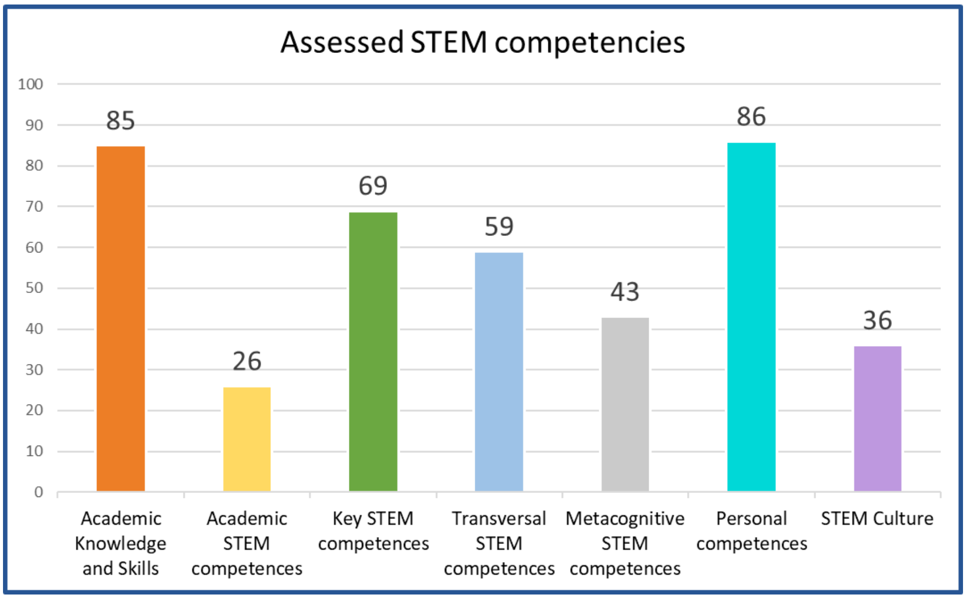

Figure 2: Tipes of Assessed STEM competences in %.

According to the obtained results, teachers mainly assessed personal competences – in 86% of the practices, and academic knowledge and skills – in 85% of the practices (Figure 2).

The distribution of the identified STEM competencies and their relevance to the Taxonomic Framework are described in Table 2.

Table 2: Distribution of identified skills assessed according to the STEM competences framework.

Categories for Analyze	Subcategories for Analyze	Identified knowledge and skills	F	% of Group	% of All
Academic Knowledge and Skills	Science	Biology Knowledge and Skills	28	37,33	31,82
		Chemistry Knowledge and Skills	19	25,33	21,59
		Physics Knowledge and Skills	8	10,67	9,09
	Math	Math Knowledge and Skills	7	9,33	7,95
	Engineering	Engineering Knowledge and Skills	4	5,33	4,55
	Technology	Digital Skills	9	12	10,23
Academic STEM competences	Structured (integrated) knowledge	Math and Engineering Biology and Chemistry Math and Physics	7	30,43	7,95
	Ampliative skills	Presentation Skills	16	69,57	18,18
Key STEM competences	Relational competences	Practical Skills	7	11,48	7,95
	Extended abstract competences	Algorithmically Thinking Critical Thinking	54	88,52	61,36
Transversal STEM competences	Problem Solving	Problem Solving	29	55,77	32,95
	Innovation and creativity	Creative Thinking Imagination	23	44,23	26,14
Metacognitive STEM competences	Independent learning	Independence	14	36,84	15,91
	Self-Regulation	Active learning	24	63,16	27,27
Personal competences	Motivation	Learning Interest Learning Motivation Curiosity	42	47,72	47,73
	Interaction	Empathy Teamwork Skills Entrepreneurship Confidence	34	52,28	38,64
STEM culture	Cultural awareness	Netiquette Internet safety	12	37,50	13,64
	Cultural behavior	Feelings Attitudes, beliefs	20	62,50	22,73

According to the statistical values the most assessed competences, described in over 30% of the studied practices, are:

- Key STEM competences: Extended abstract competences – described in 61,36% (54) of the analyzed STEM practices:
  - Algorithmically Thinking – 44,31% (39 practices);
  - Critical Thinking – 17,05% (15 practices).
- Personal competences: Motivation – described in 47,73% (42) of the analyzed STEM practices:

- Learning Interests – 20,45% (18 practices);
- Learning Motivation – 17, 05% (15 practices);
- Curiosity – 10,23% (9 practices).

- Personal competences: Interaction – described in 38,64% (34) of the analyzed STEM practices:
  - Teamwork Skills – 21,59% (19 practices);
  - Confidence – 7,95% (7 practices);
  - Empathy – 6,82 (6 practices);
  - Entrepreneurship – 2,72 (2 practices).
- Transversal STEM competences: Problem Solving – described in 32,95% (29) of the analyzed STEM practices;
- Academic Knowledge and Skills in the Field of Biology – described in 31,82% (28) of the analyzed STEM practices (Table 2).

Figure 3 shows the most frequently used methods and techniques applied to formative assessment of STEM competencies by teachers.

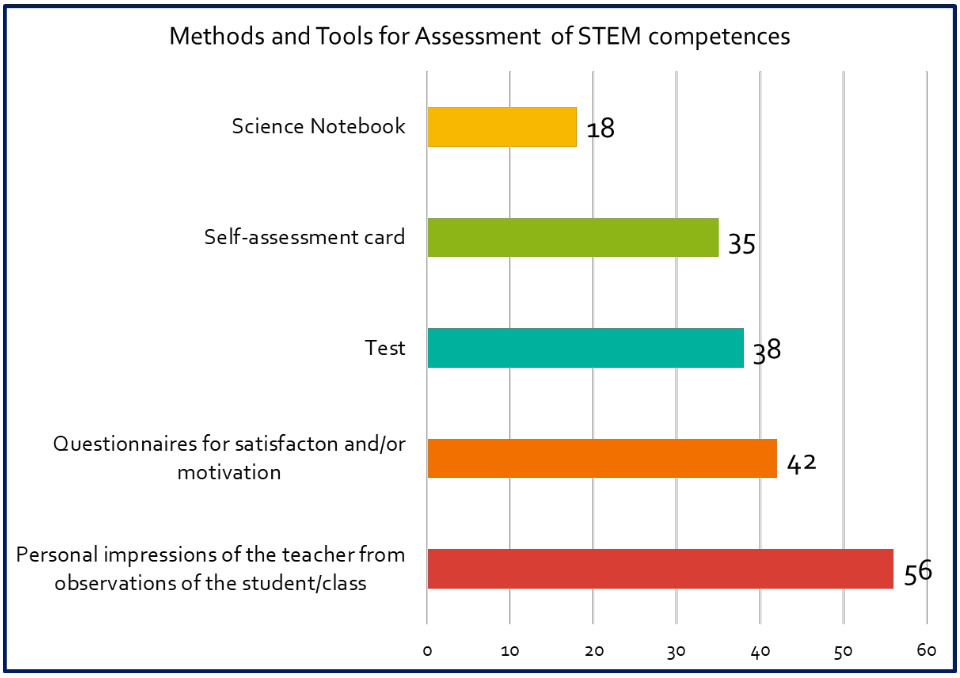

Figure 3: Distribution of used Methods and Tools for Formative Assessment of STEM competences in %.

For formative assessment of STEM competencies by students, achieved within a specific STEM practice, teachers primarily use methods and tools of a subjective nature.

In 56% of the studied cases, teachers described their own impressions from observing students' activities in STEM (Figure 3).

They often use methods to determine the attitudes, motivation, interest and satisfaction of students in STEM, such as various types of questionnaires and self-assessment cards - in 77% of the cases studied, such tools are described (Figure 3).

In 38% of the investigated cases, after the completion of the activities within a specific STEM practice, a test to assess the achieved knowledge and skills in a certain subject or interdisciplinary area is applied (Figure 3).

Methods for comprehensive evaluation of student progress in STEM, such as notebooks and portfolios, are underutilised - only 18% of the surveyed practices indicated Science Notebook assessment (Figure 3).

Conclusion

This study proved that there is a significant deficit of models and practical solutions for assessment of student achievement in STEM education.

Formative assessment is indeed given precedence, and in practical terms teachers rely mostly on observations and self-assessment of students. The instruments they use do not demonstrate sufficient reliability, which is the likely reason why students do not perform well on large-scale assessments or test scores.

Among the most often assessed STEM competencies by teachers are academic competencies in a certain subject area, which contradicts the STEM conception.

Of the key STEM competencies, those most valued are algorithmic thinking skills, which are characteristic of some of the STEM fields – mathematics, technology and engineering.

In less than 10% of the practices described, digital skills are valued, even though they are particularly important for STEM.

Problem solving is the main transversal competence that teachers assessed, innovation and creativity are underestimated.

Within the framework of personal competences, interest in learning, teamwork and motivation to learn are primarily assessed.

In more than 50% of the practices studied, the assessment is based on the personal impressions of the teacher during the implementation of the practice, in more than 40% - on the sharing of attitudes and impressions by the students through answers to questions, and in more than 30% it is based on the self-assessment of the students. This calls into question the objectivity of the formative assessment in STEM in general. Tests retain their importance for teachers, but they measure only academic STEM competencies.

Given the limitations of the research methodology, it is not exhaustive, but it is an important step towards building a strategy for deriving uniform criteria and indicators as well as for building an adaptive metric system for assessment of STEM-competences.

Acknowledgements

This study is realised with the financial support of the science project № КП-06-Н65/2. “AMS-STEM-COMP – Adaptive metric system for assessment of STEM competences in school education (1–12 grade).”

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Contact email: cpcc@abv.bg