A TAXONOMIC FRAMEWORK FOR DEVELOPMENT OF ADAPTIVE METRIC SYSTEM FOR ASSESSMENT OF STEM-COMPETENCIES

N. Kaloyanova, R. Papancheva

University "Prof. Dr Asen Zlatarov" (BULGARIA)

Abstract

The taxonomic approach entered educational theory and practice in the middle of the 20th century and proved its effectiveness in terms of constructing goals and evaluating learning outcomes. The advantage of this approach is that it enables the hierarchical structuring of goals in various aspects of educational development, resp. for systematic and objective tracking of the achievements of each student. In addition, taxonomies make it possible to develop goals for different types of instruction to measurement the achievement of learning-specific outcomes. With the establishment of STEM as an alternative educational approach, the problem of objective and reliable assessment of the results of this type of education is increasingly being discussed. The outcomes of STEM education are generally defined as STEM competencies. STEM competencies are a holistic and balanced set of academic competencies in the field of mathematics, natural sciences and technology, key transversal and personal competencies. A major problem in the measurement of STEM competencies is the variety of practical models that integrate different aspects of STEM competencies. Deficits in theory and practice arise from the need the evaluation to correspond to the fundamental educational goals of the respective educational system, and – in the same time, to be consistent with both the STEM concept and a specific STEM practice. The study presents a taxonomic framework that systematizes in a hierarchical order the achievement of STEM competence. The taxonomic framework was developed through a theoretical study that was implemented in two stages. In the first stage, a systematic theoretical analysis of data sources of research, practices and experience in developing and applying taxonomies in education was made. A standard for structuring taxonomic categories has been derived. In the second stage, specific outcomes of STEM education were identified and systematized. Based on the derived standard, a taxonomic framework was constructed that reflects the levels of STEM competencies. The taxonomic framework is documented in detail. The approach to constructing the categories and sub-categories of competences is explain, as well as their main characteristics, the upgraded value of each taxonomical construct compared to interpretations known to date, the benefits for STEM education, reflected as added value to the overall educational development of the student. The taxonomic framework is a basic for building a flexible system of criteria and indicators to develop adaptive methodological tools for measuring STEM competencies.

Keywords: STEM competencies, taxonomic framework, STEM competencies assessment, STEM metrics.

1 INTRODUCTION

The problem of measuring and assessment the student achievement in STEM relates to two main concepts – STEM literacy and STEM competence. In scientific literature, there are no specific and established definitions of the two concepts, but rather a description of their content. One of the most frequently cited explanations of STEM literacy is that of Bybee from 2013, according to which STEM literacy includes knowledge, attitudes, skills and values to identify questions and problems in life situations; to explain the natural and material world, and draw evidence-based conclusions about STEM related issues; to understand the characteristic features of STEM disciplines as forms of human knowledge, to research and design; to aware how STEM disciplines shape our material, intellectual and cultural environments; willingness to engage in STEM-related issues with the ideas of science, technology, engineering, and mathematics as a constructive, concerned and reflective citizen [1]. This expanded definition expresses the focus of STEM education over the past several decades on enhancing science and mathematics learning with little integration and attention to technology or engineering.

Building on this initial idea, in modern times is developed the so-called "integrated STEM education" which is defined as "approach to teaching the STEM content of two or more STEM domains, bound by STEM practices within an authentic context for the purpose of connecting these subjects to enhance student learning" by providing "students' support to retrieve relevant scientific or mathematical ideas in the context of engineering or technology design, to relate these ideas productively, and to reorganize their own ideas in ways that reflect norms, scientific ideas and practices" [2, 3]. The generally recognized goal of current STEM education is the advancement of well-informed and highly competent citizens; deconstructing existing social inequalities; ensuring a lawful, inclusive, and harmonized society. That is why STEM is considered as a priority of any educational policy, and the formation of STEM competences is set at school age [4].

STEM-competence is defined too conditionally as a generalized construct with many varying components that can be differentiated into two main groups: "know-what" (knowledge, attitudes and values associated with the disciplines) and the "know-how" (skills to apply that knowledge, taking account of ethical attitudes and values in order to act appropriately and effectively in a given context) [4]. From this perspective, contemporary STEM competence can be considered as a construct with three interrelated components: knowledge, skills, and attitudes in the fields of mathematics, sciences, engineering, and technology; knowledge transfer skills and metacognition and personal skills and attitudes.

In STEM education, the so-called discipline cycle is perceived holistically. Mathematics and science are both a body of knowledge that has been accumulated over time and a process (scientific inquiry) that generates new knowledge. Knowledge from science determines the engineering design process. Technology 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 [5]. This conception makes it possible to derive the following specific knowledges, skills, and attitudes for the first component of STEM competence: academic knowledge and skills in the areas of mathematics, physics, chemistry, biology, engineering sciences, technology; algorithmic, critical, and strategic thinking, problem-solving and decision-making, planning, constructive skills, technological and digital skills, research skills.

In contemporary research STEM education is considered as an interdisciplinary concept that includes integrated learning in the fields of science, technology, engineering sciences and mathematics, while providing the development of complex problems solving skills, developing innovation and design, so to achieve a sustainable person who knows how to manage and improve his/her life plan [6, 7, 8]. Therefore, the second component of STEM competence mainly includes the skills to solve problems in real life context, acting in critical situations, innovation and creativity, design thinking; emotional-social learning, regulation and self-regulation of learning, curiosity, independence, argumentation and debating skills, reflection of experience.

In several sources, STEM education is considered as supporting the development of the so-called skills of the 21st century, which include a wide range of social, emotional, and motivational skills and cultural conversance [1, 6, 9, 10]. From this perspective, the third component of STEM competence may include teamwork skills, motivation, leadership, tolerance, interests and attitudes, communication, conflict management, netiquette, Internet security and safety, cultural conversance, and behaviour.

A wide contextual understanding of STEM competence poses a strong challenge to the process of measuring and evaluating students' achievement in STEM. A review of several publications on STEM education issues shows that there are a significant number of publications devoted to the process and content of STEM education, but too few offers well-structured approaches to the measurement and assessment of STEM competencies.

In this study, a framework for developing adaptive metric systems for the assessment of STEM competencies is proposed, which is based on the taxonomic approach in education. According to this approach, in order to ensure the systematicity of the learning process, it is necessary that the goals are set and achieved by students in a certain order, starting from the easiest to achieve levels of knowledge. Usually, taxonomies differ according to their focus on a certain area of development and are cognitive, affective, psychomotor, etc. In the educational sphere, cognitive taxonomies are applied, the most widespread being that of B. Bloom et al., as well as its revised and supplemented versions, among which the most famous are those of Anderson & Krathwohl, Fraboni and Marzano [11, 12].

An overview of the most common cognitive taxonomies (Bloom, Marzano, Grunlund, D'Henault, D'Block, Ebel, Vanvelde, Fraboni, Briggs and Collins, etc.) shows that the following categories are available in various modifications [11, 12]:

- Knowledge – includes concepts, theories, facts and theoretical information from a specific or interdisciplinary field of human knowledge;
- Comprehension – refers to the interpretation, identification and conceptualization of abstract elements of knowledge;

- Application – implies the use of algorithms, rules, regulations and processes in solving learning tasks and well-structured problems;
- Analysis and synthesis – include determination of causal relationships, dependencies, elements of sets, principles, regularities; combining, summarizing, reasoning and constructing complex solutions by induction and deduction, solving more complex problems with more techniques;
- Evaluation – represents a critical evaluation of facts, theories, concepts, decisions; assessment of systems, connections, relationships;
- Creativity – includes manifestations of originality, imagination, fantasizing, finding non-traditional solutions in complicated situations.

Since the orientation of modern education is towards the formation and development of competences covering all spheres of the student's development, the so-called mixed taxonomies are becoming more and more effective. In the mixed taxonomy, the goals are integrated and systematized, covering the widest possible type of competences from different spheres of the personality – cognitive, affective, motivational, social, psychomotor. Jonassen and Tessmer emphasize that any modern taxonomy must be a comprehensive system that provides a tool to facilitate the analysis of learning tasks, the identification of learning outcomes, and the evaluation of learning systems. It should reflect the complex nature of the acquired knowledge, which in a real situation manifests itself simultaneously on a theoretical and practical level. The taxonomy should also make it possible to measure the knowledge achieved with multiple measures that reflect its diversity and manifestation in real-life situations [13]. The described premises correspond to the STEM concept and are the theoretical basis of this study.

2 METHODOLOGY

The aim of this study is to be develop a taxonomic framework that is the basis for building specific systems of criteria and indicators and developing adaptive methodological tools for measuring STEM competencies.

The taxonomic framework was developed through a theoretical study that was implemented in two stages.

In the first stage, a systematic theoretical analysis of data sources of research, practices and experience in developing and applying taxonomies in education was made. A standard for structuring taxonomic categories has been derived.

In the second stage, specific outcomes of STEM education were identified and systematized. Based on the derived standard, a taxonomic framework was constructed that reflects the levels of STEM competencies.

3 RESULTS

For the aims of the study, five taxonomies were analysed, which reflect the philosophy of stem education to the fullest extent. Through systematic analysis and synthesis, structural categories adequate to the STEM concept have been derived and adapted from these taxonomies.

From the SOLO (Structure of Observed Learning Outcomes) Taxonomy, the concept of Hierarchical Levels of Understanding is applied. In the construction of a taxonomic framework in the STEM context, the last two levels of understanding are implemented, which imply an interdisciplinary and holistic approach to the construction and evaluation of knowledge [14]:

- Relational level - knowledge is combined to form a structure linking different parts into a whole. Concepts and ideas connect and offer a coherent understanding of the whole.
- Advanced abstract level - knowledge is generalized to build a new domain, transfer and generalize concepts and principles from one subject area to another, developing new concepts and ideas based on an understanding of the task or subject being taught.

From Finks Taxonomy the idea of developing, resp. evaluation of personal and transversal skills is borrowed, which are distinguished in the last three levels of the taxonomy [15]:

- Human Dimension – learning about yourself and others, learning to change and develop future goals (self-ideal), reflective learning (self-image), learning through interaction with others;
- Caring – identifying/ changing one's feelings, interests, values towards a certain topic;
- Learning How to Learn - independent learning and use of learning techniques.

From the revised Bloom's taxonomy by Anderson and Krathwohl [16], the metacognitive level was adapted, which includes self-management of one's own knowledge, self-knowledge, self-regulation and self-development in learning activities.

From Fraboni's taxonomy, the level of higher divergent learning was adapted, which implies the expression of creativity and insightful decisions [17].

From Jonassen's Outcomes-Based Taxonomy for the Design, Evaluation, and Research of Instructional Systems, the constructed classes of criteria and their characteristics were adapted and explained [13]:

- Ampliative skills – uses rules of logic and imagination to draw conclusions, explain implications, imagine possibilities.
- Structural knowledge – a thematic set of propositions, images, concepts, or rules interconnected by various types of relationships.
- Self-knowledge – uses reflection and self-examination skills to identify cognitive and affective strengths and weaknesses.
- Situated problem solving – emphasizes problem solving in authentic performance contexts. Identifies the suboutcomes of problem solving (identification, decomposition, etc.)
- Executive control – focuses upon controlling internal learning and problem-solving processes.
- Motivation – involves the willful manipulation of task attention, effort and enthusiasm. It has distinct suboutcomes of willingness, persistence, and effort.

From the theoretical analyses, six main areas of competence can be distinguished as a result of STEM education:

- Academic STEM competences – they are fundamental for STEM education and include knowledge and skills from the fields of sciences, technologies, engineering and mathematics [2, 3, 4, 18, 19]. According to the taxonomic approach, it is the lowest level of achievement associated with arrays of information holistically combined into sets of knowledge and skills. At this level, structured (integrated) knowledge and ampliative skills are developed and measured [13].
- Key STEM competences – includes skills for divergent thinking, problem solving and decision-making, planning skills; constructive, technological and digital skills, research skills [2, 3, 4, 18, 19]. This is the next level of STEM competence. It includes relative and extended abstract levels of understanding, named relational competences and extended abstract competences [15].
- Transversal competences – transferable competences related to the transfer of knowledge and skills in other, atypical areas, as well as in real life situations [6, 7, 8, 18]. They build on key STEM competencies and are realized through skills for complex problems solving, innovation and creativity [13, 17].
- Metacognitive competences – include knowledge about one's own self, reflection of acquired experience, skills for building one's own strategies for learning and self-development [6, 7, 8]. In school education they are manifested in two main directions - independent learning and self-regulation [13, 16].
- Personal competences – include a wide range of skills based on interests, attitudes and communication, applicable in real life, which ensure prosperity and continuous development of the personality [1, 6, 9, 10]. Main features of personal competences are personal motivation and interaction with others [13, 15].
- STEM culture – covers conflict management skills, netiquette, Internet security and safety, cultural awareness and behaviour, summarized in two main categories: Cultural awareness and cultural behaviour [1, 6, 9, 10, 19].

Based on the theoretical analysis table 1 presents a taxonomic framework for development of adaptive metric system for assessment of stem-competencies.

Table 1. A taxonomic framework for development of adaptive metric system for assessment of STEM-competencies

CATEGORIES	SUBCATEGORIES	CHARACTERISTICS	DIFFERENCES FROM RELATED CONSTRUCTS	STEM LEARNING OUTCOMES
Academic STEM competences	**Structured (integrated) knowledge**	Integrative cognitive constructs involving knowledge from the fields of mathematics, physics, chemistry, biology, engineering and technology.	Cognitive constructs are not subject-specific. They are a holistic network of knowledge in several STEM subject areas and are internalized as a common concept.	Students understand the integrity of the world around them. They can independently expand the scope of knowledge and use it in different situations.
	Ampliative skills	Skills in the field of mathematics, physics, chemistry, biology, engineering, and technology that are amplified through the use of integrative cognitive constructs.	Ampliative skills are based on interdisciplinary knowledge and are more effective than learning skills because they use information in extended, combined variant.	Students apply the acquired knowledge in a variety of situations and contexts, extending their own range of skills and varying between different skills according to the situation.
Key STEM competences	**Relational competences**	Complex of constructive, digital and technological skills, expanding the amplibative ones.	Relational competences enable one to act in different situations and use more than one tool to find solutions.	Students use a structured set of steps and solutions to complete complex learning procedures.
	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).	This type of thinking, based on complex sets of knowledge and skills, enables the generation of new ideas and the construction of effective cognitive strategies.	Students develop thinking with a high degree of flexibility, resourcefulness, criticality and creativity.
Transversal competences	**Problem Solving**	Solving authentic problems with multiple methods and techniques, incl. in a new, non-standard context.	Problem solving is based on discovering (heuristics) multiple possible solutions.	Students solve problems through discovery and generate different solutions using a variety of methods.
	Innovation and creativity	Higher divergent / lateral thinking. Approbation of solutions, search for alternatives, construction of hypotheses, insight and creativity.	Includes generation of non-standard solution ideas, incl. discovery of new research approaches and products.	The students demonstrate innovation, non-standardness, extraordinary when solving problems in a new, non-standard context.
Metacognitiv e competences	**Independent learning**	Applying strategies emotional-social learning, argumentation and debating, curiosity and independence, learning to change.	Deep understanding and awareness, incl. by accepting other points of view. Integrating the newly acquired knowledge and skill sets into the overall experience.	Students learn independently in a variety of contexts, incl. through expressing an opinion, building argumentative theses, arguing and empathizing.

	Self-Regulation	Reflection of experience, regulation and self-regulation of learning, independent finding of solutions and answers to dilemma questions and problems.	Reflection of experience, regulation and self-regulation of learning, independent finding of solutions and answers to dilemma questions and problems.	Students master different forms of self-regulation in a different learning situations.
Personal competences	**Motivation**	Demonstration of motivation, interests and sustainable attitudes towards learning and development in the field of STEM.	Sustained motivation and attitude to learn in STEM, incl. to seek alternative solutions and deal with current problems.	Students are motivated to learn through and about STEM.
	Interaction	Manifestations of teamwork, leadership, tolerance, communication, dealing with conflicts in real situations, learning through interaction with others.	Building a learning and developing community.	Students show empathy for the school and other communities.
STEM culture	**Cultural awareness**	Use of netiquette, tools for Internet security and safety in the context of global and uncontrolled communication.	Manifestation of individual and collective behaviour of communication and learning in the global space (real, virtual).	Students use a global space to communicate, learn and exchange ideas.
	Cultural behavior	Identifying/changing one's feelings, interests, values in a STEM context.	Manifestation of a comprehensive culture of behavior. Reconciliation of STEM behavior in real-life settings.	Students exhibit sustainable behavior in the dynamic real environments.

4 CONCLUSIONS

During the development of the standard for structuring the taxonomic framework, the following requirements were observed:

- To be a complete system for developing a toolkit for measuring STEM-competencies, reflecting the hierarchy of achieving the goals - on the one hand, and on the other - the possible options for the manifestation of each competency in the specific STEM practice;
- To clearly describe the distinguishing features of individual taxonomic categories and subcategories at two levels: definition and characteristics of the category and outcome achieved (benefits for students);
- To enable the development of specific performance criteria (measurement indicators) depending on various factors determining the STEM practice – e.g. age, type of school, subject focus, etc.;
- To reflect the variety of behavioral manifestations in which a given knowledge, skill or attitude can manifest itself;
- To specify the building effect of STEM education compared to traditional education;
- To give guidance on the expected performances of the students with a view to structuring indicators to measure its achievements within STEM;
- To enable research and development of STEM learning in different educational contexts.

The framework can be used in various aspects of the implementation of STEM education, but with a focus on defining specific goals, resp. development of accurate criteria, indicators and accompanying adaptive metric toolkit for assessment of achieved STEM competencies.

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