Development of STEM skills and competencies through object-based STEM learning

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Abstract
Developing STEM competencies is a key topic in the education system in the EU and beyond. Many studies have proven the importance of Competence-Based Education (CBE) and its methods applied in the classroom. In recent years, research on problem-based and project-based learning in STEM has been extensive. This study aims to propose a new method for the development of STEM competencies, "Object-Based STEM Learning" (OBSL). The study provides a brief overview of STEM skills and competencies, as well as conceptual thinking skills. The OBSL method is a system thinking approach for non-linear learning. The method includes 4 stages, detailed and structured in the OBSL process. The study proposes a definition of OBSL and instructions for designing an OBSL lesson that can be used by teachers when implementing the method in the classroom. The study concludes with some principles for effective OBSL, as well as future research steps.

Keywords: STEM, object-based, skills, competencies, learning.

1. Introduction
STEM stands for Science, Technology, Engineering and Mathematics. STEM was primarily used in engineering firms to produce revolutionary technologies such as light bulbs, automobiles, tools, machines, etc. [1]. Through the years, many researchers and practitioners have been trying to find the most usable STEM methods and frameworks. Many analyses have been conducted about the most appropriate STEM definition, to be used in practice and ease STEM understanding. STEM education focuses on technical skills, while STEAM emphasises creativity and critical thinking through the Arts. Both aim to develop 21st-century skills like problem-solving, adaptability, and innovation. STEM education challenges include unclear definitions, lack of empirical evidence on effectiveness, and varying educational approaches. Current studies are often limited [2].

The most popular approaches for STEM learning are problem-based learning, project-based learning, and inquiry-based learning. Problems in problem-based STEM learning should encourage speculation and discussion and motivate students' need to learn. The problems have to be related to real-life, industrial, and business practices, as in this way they're a precondition for developing skills necessary for the labor market. Research shows, that there is huge labor market demand for STEM skills and competencies, such as problem-solving skills, out-of-the-box thinking [3], team working, etc. Research by The European Centre for the Development of Vocational Training shows the qualifications needed for a job in the EU by sector (Figure 1).

For example, O*NET system is maintained by a regularly updated database of occupational characteristics and worker requirements information across the U.S. economy. It describes occupations in terms of the knowledge, skills, and abilities required as well as how the work is performed in terms of tasks, work activities, and other descriptors [4] [5]. Many occupations require education in STEM disciplines. STEM occupation data comes from the Standard Occupational Classification (Figure 2) [6].

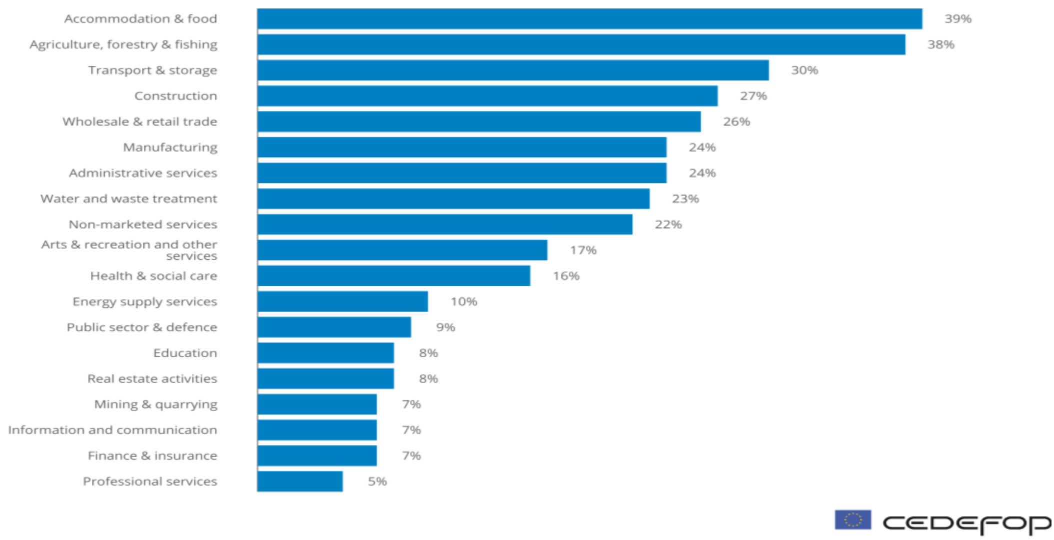

Fig. 1. Qualifications needed for job, Scope: EU27 [7]

Each STEM occupation is described based on 7 groups of characteristics:

- Occupation-Specific Information – overview, tasks and technology skills;
- Occupational Requirements - work activities, detailed work activities, work context;
- Experience Requirements - job zone, training & credentials, apprenticeship;
- Worker Requirements – skills, knowledge, education;
- Worker Characteristics – abilities, interests, work values, work styles;
- Workforce Characteristics - wages & employment, job openings;
- More Information - related occupations, professional associations.

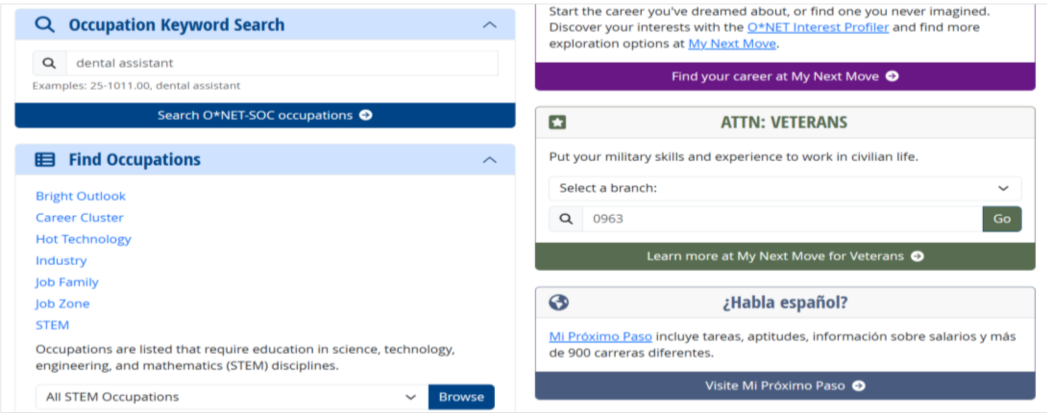

Fig. 2. O*NET system

This research aims to propose a new STEM learning method, “Object-based STEM learning”, which adds value to the traditional STEM methods, by more engaging learning scenarios, more learning activities, and a deeper thinking model, while developing concept-thinking skills and out-of-the-box thinking of students. The study analyses are based on a literature review, desk research, and statistics analyses.

2. STEM skills and competencies

Competence is viewed as a measurable ability of a person to act qualitatively and effectively to deal with specific problems, events, or tasks that arise in a specific situation and ecological niche (study, work, sports, etc.). David McClelland views competencies as indicators of workplace performance [8]. Michael Zwell understands competencies as enduring traits and characteristics that determine performance [9]. According to Lyle M. Spencer, competencies are the internal characteristics of a person that allow them to perform better in a given task, role, or situation [10].

Table 1. Competence vs Competency

Competence [Competences (pl.)]	A noun – The ability to do something successfully or efficiently
Competency [Competences (pl.)]	An action – A behaviour, skill or use of knowledge.

According to S. James Gates, active engagement is key to teaching STEM [11]. If the students are engaged across many different levels, including collaborative research and collaborative learning, this is a far more effective way to teach the people who are entering STEM disciplines[5]. STEM learning and STEM

[5] S. James Gates is a physics professor and director of the Center for String and Particle Theory at the University of Maryland, USA2

competencies are part of the STEM Education portfolio (Figure 3). Through STEM learning [12], students develop key skills including:

- problem solving;
- creativity;
- critical analysis;
- teamwork;
- independent thinking;
- initiative;
- communication
- digital literacy.

Problem-analysis and problem-solving competence are among the most important STEM competencies within STEM. They are defined in Harvard University Competency Dictionary [13] as using sound or logical judgment to spot and analyse problems, develop alternative solutions, and initiate corrective action. Key actions for competency demonstrations are:

- Proactively identifies problems – anticipates, identifies and clearly defines problems;
- Identifies multiple solutions to the problem – identifies, evaluates and weighs alternatives of multiple solutions;
- Proposes and implements solutions – works effectively with the organization to resolve issues and proposes and implements well-conceived, logical solutions in the best interest of the organization.

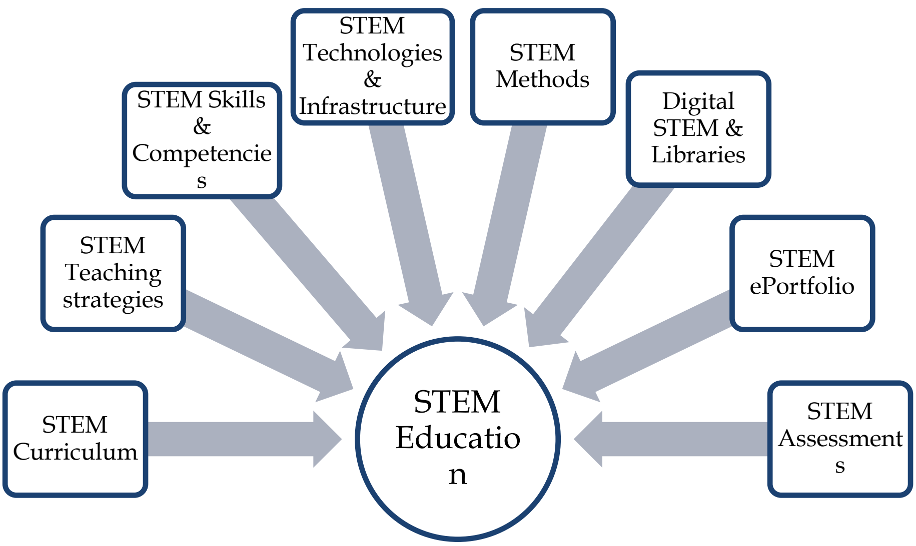

Fig. 3. STEM Education portfolio

STEM learning is team-based work, and it is based on solving real-life problems (formal and non-formal settings). The learning activities and instructions by the teachers aim to encourage students` interdisciplinary thinking [14]. Questions, that can be used by the teachers to develop interdisciplinary thinking, are:

- Can the principles of … be applied to ….?
- Is there a difference between …… and …..? Why?
- What would happen if we replace …. with ……? Will we get the same results from the work/process/…?

A study examines the relationship between STEM education and the development of children's mathematical abilities, which are manifested in spatial abilities. A cross-subject approach is used. Experimental groups are randomly assigned, in which one group participated in STEM training twice a week for two months, and the other group participated regularly. Results have indicated that STEM education was associated with significant spatial ability improvement in children aged 5 to 6, especially in children with intermediate or lower mathematical ability [15]. Research shows that STEM education is focused on the interactivity of the learning process, aimed at acquiring knowledge and developing competencies by solving real-life problems that arise in the different industries – healthcare, transportation, agriculture, etc., in nature and space. In each of these industries, design and concept development is one of the key stages. There is no research about STEM conceptual thinking competency development and how it can be encouraged in STEM learning scenarios.

3. Concept-thinking skills

Concept development requires concept thinking skills. Such skills can be integrated into the STEM learning instructions, which teachers give to students. Concept thinking skills develop students` ability to think outside the box and explore creative, seemingly unfeasible ideas. For example, the concept connection strategy has been applied in Geography subjects, where students ought to connect one concept with another concept to form a concept that they understand completely, especially in material about the Flora and Fauna of Indonesia and the World [16], [17]. Through the creation of concepts, the students can also develop critical thinking to experience the world [18].

ESCO is the multilingual classification of European Skills, Competences, and Occupations. The ESCO classification identifies and categorises skills, competencies, and occupations relevant to the EU labor market and education and training. It systematically shows the relationships between the different concepts [19]. ESCO proposes different definitions related to the term “Concept thinking” (Table 1).

Table 2. Concept thinking related skills

Thinking	Ability to apply mental processes to solve complex problems and achieve goals, to acquire knowledge and to perform complex tasks.
Design thinking	The process used to identify creative solutions to problem solving, by putting the user at its core. The five stages approach-empathise, define, ideate, prototype and test are meant to challenge assumptions and iterate solutions that are better suited to the needs of the user.
Systems thinking	The integrated approach to understanding how various constituents of a system interrelate, interact and influence one another within a whole logistic system
Apply conceptual thinking	Identify patterns and connections between situations; identify key issues in complex situations.
Thinking creatively and innovatively	Generate new ideas or combine existing ones to develop innovative, novel solutions.
Thinking skills and competences	Skills and competences relating to the ability to apply the mental processes of gathering, conceptualizing, analysing, synthesizing, and/or evaluating information gathered from, or generated by, observation, experience, reflection, reasoning, or communication. They include the ability to evaluate and use information of different kinds to plan activities, achieve goals, solve problems, deal with issues and perform complex tasks in routine and novel ways.

The term "conceptual thinking" is used to describe ways of thinking that explore equivalence-of-meaning representations and patterns of associations among ideas, relations,and underlying issues [20]. There are many digital tools applicable to STEM learning and concept thinking skills development, such as EdrawMind [21], MindMeister [22], Zapier [23], etc. For example, Mind mapping is a powerful technique that helps students visualize thoughts and communicate them to others. MindMeister's easy-to-use, web-based mind mapmaker provides an infinite canvas for brainstorming, note-taking, project planning, and other creative tasks, with no download required. Using such tools, the traditional learning process can be significantly improved. The improvements can be not only using STEM methods for developing creativity, interdisciplinary thinking, concept thinking skills, etc. but also curiosity can be encouraged.

4. Object-based STEM learning

Definition: Object-based STEM learning (OBSL) focuses on interdisciplinary skills and the development of conceptual thinking skills, which involves combining two or more academic disciplines in STEM learning scenarios. OBSL adds value to the STEM learning process by studying objects, while focusing learners' attention on developing the concept of the objects and applying knowledge from different disciplines to the objects.

In the traditional learning, the learning is linear. OBST is a system thinking approach and non-linear learning (Figure 4).

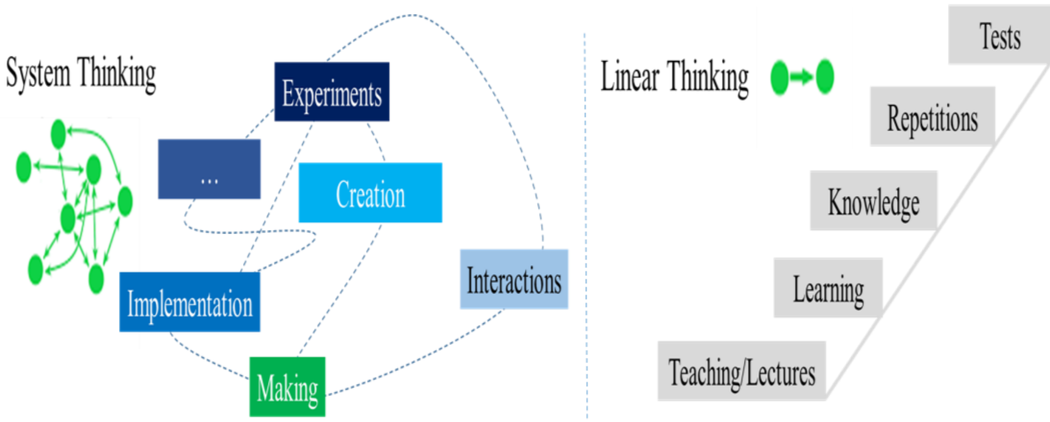

Fig. 4. OBSL Systems thinking abstract model

The main principle of OBST is that the students are actively involved in the learning process and perform different learning activities. The activities are instructions by the teacher to the students. The teacher has the role of moderator. The object of OBST is:

- defined by the teacher before the lesson;
- from the real life;
- part of a learning resource (video (max 2 min), multimedia, infographic (A2, A1), podcast (max 2 min), etc.)
- given by the teacher to students at the beginning of the lesson.

Table 3. Object-based STEM Lesson design

Stages	Instructions
Define a name for the object-based STEM lesson.	The lesson name should be challenging and intriguing for the students.
Formulate learning objectives.	Objectives include competencies from one or more STEM occupations/jobs, according to the grade and age of the students.
Define the STEM object. Think of a problem to be solved.	The object is one word. Objects (things that can be produced – product/service) can be more than one. There is no limitation about the object, or what it can be.
Develop learning activities and instructions.	Research; Analyze; Create a concept; Discuss; Compare; etc. (Bloom's Taxonomy [24])
Plan and provide materials and knowledge resources	Prepare materials according to the objectives and time of the STEM lesson.
Assessment - create a simplified assessment matrix for assessment and self-assessment.	The assessment criteria should be explained to the students before the lesson. The assessment should be simple.
Create Time framework	Depends on the object`s complexity

The OBSL has four stages of implementation.

- The first stage "**Object discussion**" is presented in Figure 1.

Fig.5. OBSL Stage 1 – Object discussion

Students must formulate pertinent inquiries to comprehend the object and discern pertinent patterns, dependencies, and laws from the educational material applicable to the object. Educational material may include, for example, trigonometry functions from Mathematics; the Pythagorean theorem in Mathematics; and Newton's second law of motion in Physics. The educational material is/can be from the students' textbooks. It is aligned with the grade and age.

- The second stage "**Concept map development**" includes two phases:
  - The students identify the object;
  - The students are asked to create a concept map of the object.

Students work in teams and try to create a concept map of the object. The teacher stimulates students by encouraging them to think interdisciplinary. The students can create as many concept map lines as they think the map will present the object in the best way and detail.

- The third stage, "**Knowledge understanding**" connects the object with the study material in the lesson. The learning activities are as follows:
  - The students discuss how the new knowledge is related to the object.
  - The students understand new knowledge more easily.
  - The teacher gives the students one STEM problem to solve using the new knowledge.
- The fourth stage "**STEM Problem-solving**" includes the following learning activities:
  - The students discuss the possibilities for solving the STEM problem using the understood knowledge;
  - The teacher encourages the students to find more solutions to the problem;
  - The students are solving the problem;
  - The students demonstrate the solution of the problem;
  - The students discuss how the principles used to solve the problem can be applied to other objects from life;
  - The teacher asses the students' work using an assessment matrix.

In Figure 6 the process of OBSL is presented.

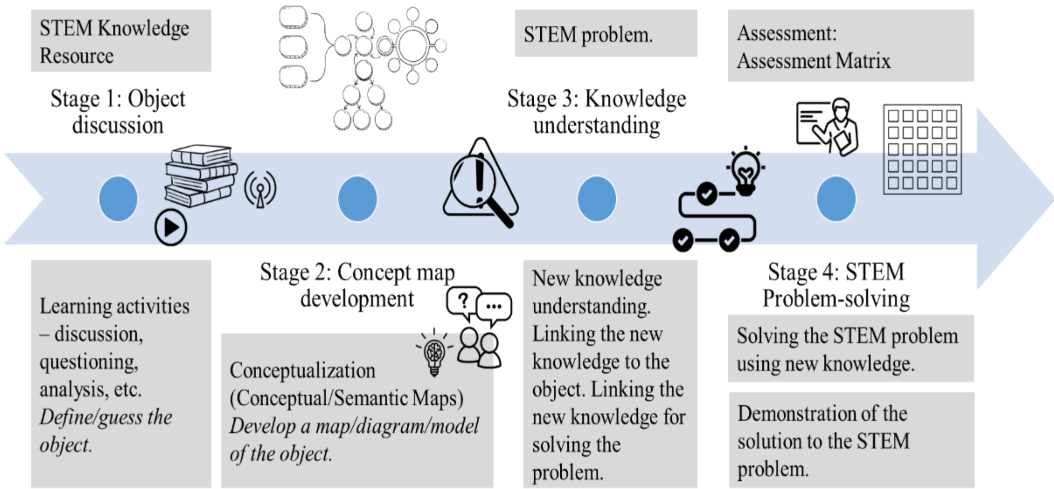

Fig. 6. Process of the Object-based STEM Lesson model

The teachers need to plan OBSL and prepare knowledge resources in different formats - videos, infographics, podcasts, etc. The application of the method requires teachers to collect real-world examples of an object/s and to consider how students can develop knowledge and skills through studying the object (For example: cup, key, motor, etc.) and to prepare questions for discussion. During the implementation of OBSL, the teacher has the role of a moderator who encourages students' small successes.

The OBSL is an excellent method for the development of interdisciplinary and concept thinking competencies, but also for the development of many 21st-century skills. It allows the development of critical thinking in STEM projects, teamwork skills, long-term thinking, cross-disciplinary thinking, proper listening, speaking, and writing. The method allows applying the trial-and-error approach.

5. Conclusion

There is a huge evolution of STEM Education in Europe and the World. Although much research has been done in this field, this study proposes a new Object-Based STEM Learning, which enhances students` curiosity - an emotion associated with natural behaviors such as exploration, research, and learning. OBSL is developing interdisciplinary and concept-thinking competencies. In real life, in each industry sector (production of products and services), as well as in the engineering processes design, concept development is one of the key and very important stages. That's why the OBSL possesses huge benefits for education and the practice and the competencies demanded in the labor market.

Some principles must be considered for effective implementation of the OBSL method. This is setting a lesson topic with a provocative name, as well as setting learning objectives – knowledge, skills, and competencies that students should acquire. The context of the topic is also important, as well as which STEM profession(s) it falls into, as well as what real-world situations can be given as examples. It is also necessary to determine the way to demonstrate the skills and competencies. The implementation of the OBSL method requires the creation of a collection of "Objects" tailored to the age group and subject area, as well as brief instructions for the lesson. The creation of a simplified assessment matrix and time frame will contribute to the effective implementation of the method and the objectivity of the assessment.

The next research steps will be related to the implementation of OBSL in the classroom, analysing the feedback and answering the research questions "What is the perception of students about OBSL? Are students more motivated in the OBSL learning process? Can the STEM ePortfolio be applied to demonstrate the acquisition of STEM competences?".

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