STEM Education:
Key Challenges in the Common Practice

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ABSTRACT

The purpose of the study is to analyze the key challenges in the implementation of STEM education in Russia and the largest economies in terms of employment promotion and increasing student competitiveness. The research is based on the system analysis aimed at assessing the current status of STEM education in Russia and highlighting its key problems, and the comparative analysis is focused on comparing the approaches to STEM education implementation in Russia and other countries. It has been shown that STEM approach is being most actively implemented in the American system of education, which attracts young people to STEM careers through state and non-formal STEM education programs. The research describes a scheme of cooperation and partnership between stakeholders and the federal coordinating body of the Russian Federation providing support for the STEM education and aimed at the interaction between state and public institutions.

KEYWORDS

Engineering Education, Key Challenges in the STEM Approach Implementation, Principle of Integration, Stakeholders, STEM Education

INTRODUCTION

The transition to a new technological order will lead to the emergence of completely new large markets in the next 10-20 years that will offer consumers advanced technological solutions and innovative products and services (Kulbyatskaya, 2017; Zhang & Niederman, 2017). Accordingly, the Fourth Industrial Revolution will soon require new quality and personnel qualifications, as well as staff retraining (Zhang & Niederman, 2017). Therefore, today the focus is being placed on STEM education in Russia and around the world. To sustain competition in the scientific and technological sphere, the Russian Federation should introduce engineering education and at the same time enhance the professional development of graduates. To accomplish this task, the Ministry of Science and Higher Education of the Russian Federation decided to introduce changes in the educational process. The active introduction of STEM education in educational institutions can be one of the ways to increase the interest of engineering students in learning and scientific activities (Sabirova et al., 2020).

STEM is an acronym used to describe scientific and technical areas in education and production. Thus, S stands for *science*, T – *technology*, E – *engineering*, M – *mathematics* (Grigoriev & Kurnosenko, 2018). The concept refers to the features of the didactics reflected in a combination

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of interdisciplinary practice-oriented approaches to the study of natural sciences and mathematical disciplines (Noor et al., 2021). Even though in modern science there are different approaches to STEM education, researchers agree that it is an innovative educational phenomenon that implies a new process of acquisition and assimilation of knowledge related to scientific, technological, engineering, and mathematical fields. Its purpose is to prepare graduates for professional activities, in particular, for performing professional tasks and solving problems through the acquisition of scientific thinking skills and the development of STEM competencies.

Today STEM education is a priority in many countries. In Russia, the trend is getting widespread within the framework of the National Technological Initiative (NTI) with the support of the Council for Economic Modernization and Innovative Development, the Ministry of Science and Higher Education of the Russian Federation, the Institute of Pedagogy and Psychology of Education, as well as the representatives of leading high-tech Russian and foreign companies and large business associations of Russia. Due to the versatility and complexity of the phenomenon, it takes a certain amount of time to solve the problems associated with the introduction of new curricula in educational institutions, as well as with the creation of conditions for STEM projects implementation. A significant advantage of STEM education is the interdisciplinary approach to teaching, which makes it possible to acquire knowledge from various sciences and use them in the study of other disciplines of the humanities, sciences or technology (Shukshina et al., 2021).

The key problems of introducing STEM education in the top countries of the world and the prospects for its development in Russia are highlighted in foreign (Kanadlı, 2019; Martin-Hansen, 2018) and Russian research (Frolov, 2010; Kulbyatskaya, 2017; Rudskoy et al., 2017b). Separate studies are devoted to STEM education with the elements of problem-based learning aimed at the improvement of student research skills (Duda et al., 2019; Grigoriev & Kurnosenko, 2018; Hadiati et al., 2019). The relevance of STEM education in terms of employment opportunities in the context of high-tech industries development is considered by both Russian scientists (Repin, 2017; Vodolazhskaya et al., 2018) and foreign researchers and practitioners (Kim & Keyhani, 2019; Jamaludin & Hung, 2017). The studies on the involvement of women in STEM careers, their appropriate training, employment and the problems that arise during these processes are also relevant from the perspective of gender parity (Mansfield et al., 2014; Pelch, 2018).

STEM education can be defined as a holistic approach which allows students to transform the knowledge and skills acquired through science and mathematics into an engineering product with the help of technology (Kanadlı, 2019). At the same time, STEM education programs include practical tasks aimed at balancing theory and practice with an emphasis on the practical component in the study of academic disciplines (Nepeina et al., 2020). STEM education programs provide an opportunity to develop technical skills in the use of modern technologies, including online educational platforms with online courses and functionality for classes (Chirikov et al., 2020). When exploring the compatibility of the new STEM approach with the old traditional one, it should be noted that the problem is not only the decision to rebuild the education system but also the readiness of the conceptual and institutional grounds for this, namely the development of new curricula and subjects, new organizational structure and standards (Vodolazhskaya et al., 2018). The use of one of the methods of STEM education – problem-oriented laboratory work – allows students to most effectively improve their research skills (Hadiati et al., 2019). Tinnell et al. (2019) determine the study of the ways to improve the teaching of STEM disciplines in the educational institution as a priority approach to the development and improvement of professional STEM competencies. The leadership of engineering institutes with the support of their faculties creates centers aimed at improving the quality of engineering education. These centers contribute to the professional development of teachers, the formation of skills to properly teach STEM disciplines to engineering students. In addition, the Accreditation Board for Engineering and Technology (ABET) located in the United States believes that two out of the seven required student learning outcomes described in the engineering curriculum ensure an effective collaboration of graduates with stakeholder employers. The two outcomes directly related to the student willingness to cooperate are effective teamwork and communication skills. Employers expect graduates to be ready to collaborate in teams, but they also note that the priority of developing these skills in engineering students is currently not fully understood by educational institutions (Tinnell et al., 2019).

The engineering industry is often defined as a path to lifelong learning rather than an event that occurs only in a university environment. The U.S. National Academy of Engineering (the Engineer of 2020: Visions of Engineering in the New Century program) and the ABET, an independent accreditation body for engineering programs in the US, have together identified a wide range of qualities and abilities that are vital for the engineers of a new era. They include continuous self-learning, creative work across disciplines, practical ingenuity and, in addition to technical expertise in engineering fields, the ability to communicate with a wide audience of clients. These qualities are important for a variety of practical engineering activities (Foster et al., 2018).

At the same time, there is a lack of research devoted to the problems of employment in modern STEM industries, as well as to the issues of effective interaction of state and public institutions with centers providing STEM education in Russia. Thus, researchers studying the above problems have revealed a number of serious problems and contradictions:

- The traditional and conservative paradigm of education based on the knowledge model (focused on the priority of knowledge) does not fully meet the requirements and demands of education and training in the 21st century on the part of the state and leading technology companies, i.e., there are certain problems of the system of teaching modern students science, technology, engineering, and mathematics.
- Researchers note a decrease in motivation when studying STEM subjects and choosing a career of this type; there is a low level of academic performance in physics and mathematics, as well as a lack of ability to effectively solve real problems that require the knowledge of STEM disciplines and the application of practical skills.

The quality of basic STEM education is poor and there are no STEM laboratories, student startups and other conditions for the development of STEM skills in engineering students in many educational institutions.

The content of STEM teachers training is not aimed at studying the approaches to implementing interdisciplinary interaction and technologies for project-based and phenomenon-based learning.

These shortcomings can lead to a decrease in the number of skilled workers (shortage) in STEM industries. The shortage of scientific and technical personnel will further threaten Russia's national competitiveness. The above facts determined the choice of the research topic.

The purpose of the study is to analyze the key challenges in implementing STEM education in Russia and the largest economies in terms of the employment promotion and increasing students' competitiveness. The research objectives are as follows:

- To substantiate the priority of STEM education in the conditions of the modern and predictable global labor market;
- To identify the features of STEM education in the context of forming skills and abilities as a modern approach in high-tech industries development;
- To define a list of key problems accompanying the implementation of STEM education in the world practice;
- Based on best practices, to trace possible and practical solutions to the key problems of STEM education implementation in Russia;
- To analyze the potential and specifics of cooperation and partnership between stakeholders and the federal coordinating body providing support for STEM education in Russia.

Methods and Materials

To achieve the research goal and solve the research objectives, a set of research methods determined by the specifics of the study material was used, namely:

- the theoretical analysis of scientific literature, synthesis, induction and deduction, comparison, analogy, and matching techniques in order to clarify the degree of elaboration of the problem, determine the theoretical foundations of the study, analyze the conceptual (categorical) apparatus of the study;
- generalization and systematization of conceptual aspects for the development and substantiation of conditions to ensure training based on the STEM approach in the educational institutions of Russia;
- special research methods, including systems analysis to assess the current status of STEM education in Russia and highlight its key problems;
- comparative analysis in order to compare approaches to STEM education implementation in Russia and in the world practice.

The study is based on the statistical data that reveal the status of STEM education in Russia and foreign countries. Thus, the study also relied on the data provided by the Federal State Statistics Service of Russia and related to the situation in the labor market over the period of 2017-2018 (Surinov, 2018, 2019), according to which employment in STEM industries (professional, scientific and technical activities) increased from 3.8% (2718.9 out of 71746.2 people employed in all industries) in 2017 to 4.0% (2836.4 out of 71726.3 people employed in all industries) in 2018. It is important to note that in the data of the Federal State Statistics Service of Russia until 2017, this type of activity (and related employment) was not considered as a separate one.

As STEM does not relate only to education but also includes the professional sphere, the data on the specifics of the global labor market, in particular, vacancies that relate to high-tech STEM industries, are relevant in the aspect of the study. The *Change the Equation* Inc. conducted a study which revealed that in the United States, there are on average 1.9 open STEM jobs per one potential employee (see Table 1). By contrast, in other industries, there are approximately 3.6 unemployed per job opening (Change the Equation, 2018).

Table 1. The comparison of STEM education features in the USA and other countries

USA	Other countries
Engineering and scientific skills are the conceptual foundation of the STEM education program	The development of creativity and critical thinking is more preferable
Average 1.9 open STEM jobs per one potential employee	Approximately 3.6 unemployed per job opening
STEM education system is represented by health care, computer science, social science, engineering, life & physical sciences	STEM education is represented by science, technology, engineering, mathematics
The standards are focused on the understanding and application of knowledge rather than the memorization of facts	The standards are focused on the memorization of facts rather than the understanding and application of knowledge

High demand for STEM professionals is expected by 2026. In particular, according to the US Bureau of Labor Statistics, the demand for *health care* will grow by 21.5%, *computer science* – 11.6%, *social science* – 11.1%, *engineering* – 9.3%, *life & physical sciences* – 8% (Barrick & Bock, 2018).

Results

The implementation of STEM education significantly affects students' professional orientation, as well as the formation of important competencies and skills. The principles of STEM education, which involve the unification of various disciplines and the widespread use of the project-based approach, as well as the leading principle of integrating natural and exact sciences (primarily mathematics), technology, and engineering, are transforming the educational process. The use of the integration technique allows for the modernization of the methodology, content, and volume of the educational material of natural and mathematical disciplines, technologization of the learning process, the formation of new educational competencies, as well as high-quality training of graduates to be successfully employed and to continue learning.

Classes conducted with the use of STEM technologies involve students in the demonstration and discussion of presentations, which develops students' skills of presenting projects and arguing their applied significance, teaches them to connect theoretical research with practice, to show scientific independence, purposefulness, and focus on results. Thus, professional competencies are formed, and the educational process is as close as possible to the realities of future research and professional activities.

Modern STEM education is focused on technologies that are relevant not only at the moment, but also important for professions, the significance of which is still being formed. In other words, STEM education is focused on both the modern labor market and the predicted one.

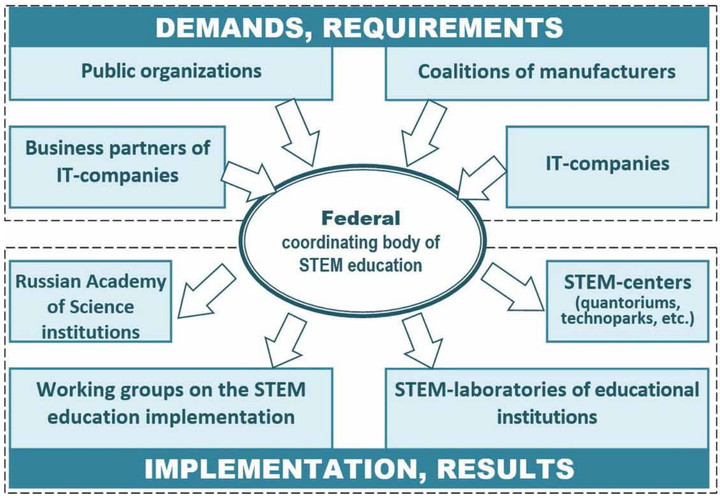
Career guidance projects as a response to the challenges of the new era involve attracting young people to knowledge-intensive STEM industries: neuroelectronics, robotics, bioelectronic medicine, neurobiology, mathematical programming, cyber engineering, etc. This contributes, on the one hand, to the improvement of the quality characteristics and efficiency of the use of human capital, and on the other hand, to the satisfaction of stakeholders' needs in the labor market.

When considering the implementation of the STEM approach in education, it should be noted that the most active state STEM programs are being introduced in the United States. In 2013, a new three-component natural science education standard was introduced: *Practices* (scientific and engineering skills), *Content* (basic subject knowledge), and *Crosscutting concepts* (generalizing skills) (Lyublinskaya, 2014). Then, eight basic scientific and engineering skills and competencies were identified (Grigoriev & Kurnosenko, 2018). Engineering and scientific skills are the conceptual foundation of the program. The standards are focused on the understanding and application of knowledge rather than the memorization of facts. Engineering skills are included in science teaching. They are given the same importance as the scientific method of cognition. Thus, the main ideas of engineering and technology education are assigned the same status as the main ideas of scientific disciplines (Lyublinskaya, 2014).

The issues related to STEM education in the United States are considered at various levels, including the federal one. In accordance with the STEM Education Coordination Act of 2009, a Committee has been created under the National Science and Technology Council to coordinate federal programs and activities in the field of support for STEM education, including the programs of the Department of Energy, STEM programs of NASA, programs of the National Oceanic and Atmospheric Administration, programs of the Department of Education and other federal agencies (Rudskoy et al., 2017b). In recent years, the STEM approach has also been introduced into modern Russian education as an innovative method recognized throughout the world. An important role in promoting STEM innovations in education is played by the establishment of effective partnerships between Russian educational institutions and key stakeholders. The concept of *stakeholder* appeared in Russian pedagogical and sociological discourse only a few years ago.

Today in Russia one can distinguish the following groups of stakeholders that are interested in the implementation of STEM education: state institutions (such as the Council for Economic Modernization and Innovative Development, the National Center for the Development of Technologies and Basic Elements of Robotics), public organizations, coalitions, business partners, and sponsors of educational institutions, out-of-school institutions, educational centers, powerful technology companies. The authors believe that in order to solve the key problems it is necessary to strengthen the relationship between various stakeholders of STEM education and the federal coordinating body in the field of support for STEM education, which can be described as a diagram (Figure 1):

Figure 1. Cooperation and partnership of stakeholders and the federal coordinating body in the field of support for STEM education



Source: own development

The study of the Russian Federation legislation and the regulatory framework in the context of the STEM education implementation has identified the key problem, which is the lack of state programs. There is also a lack of coordination between the established and operating STEM centers, Working Groups on the implementation of STEM education, and state institutions and public organizations interested in the early implementation of STEM education.

Despite the fact that the creation of a federal coordinating body in the field of support for STEM education was initiated by clause 39 of the Strategy for the development of engineering education in the Russian Federation for the period up to 2020, approved in 2017 (Rudskoy et al., 2017a), today there is no coordinating body that supports STEM education. Its functions are partially performed by:

(1) Coordination Council in the field of Engineering, Technology and Technical Sciences Education, which includes more than 30 members representing the Ministry of Education and Science of the Russian Federation, higher educational institutions of the Russian Federation, the Union of Industrialists and Entrepreneurs, Federal Educational and Methodological Associations.
(2) The interdepartmental working group under the Presidium of the Council of the President of the Russian Federation for the modernization of the economy and innovative development of Russia coordinates the interaction between state institutions, organizations, centers, and working groups implementing the National Technology Initiative (NTI) – a long-term comprehensive program aimed at the creation of conditions for ensuring the leadership of Russian companies in new high-tech markets that will shape the structure of the world economy in the next 15-20 years.

Another key problem that should be considered is the lack of scientific training of professionals involved in STEM industries. STEM workers have to engage in scientific work, including experimental research. Thus, a modern representative of the STEM profession is, first of all, a scientist.

Among modern scientific requirements, it is necessary to highlight the following skills and competencies:

- The ability to cooperate in various scientific areas.
- The ability to communicate one's own ideas to various stakeholders who make decisions about their financing.
- The ability to effectively transfer knowledge, i.e., scientific training of the next generations.

Therefore, over the past decades, career resumes of scientists have been expanded. They should not only be able to create a scientific product but also understand the specifics of the field and research methods; scientists need to know how to train laboratory personnel, perform cataloging activities, fill in proposal forms, present results to different audiences, collaborate with foreign colleagues, etc. Thus, in order to address the key problems of training STEM professionals, it is necessary to significantly increase the requirements for the quality of STEM education on the part of all stakeholders.

Discussion

An important element of the scientific discussion regarding the implementation of STEM education in the Russian Federation is the clarity of the conceptual apparatus. The study of the scientific interpretation of the elements that make up the STEM acronym shows certain discrepancies among researchers that are related to its translation and perception, for example, *Science* can be defined as general science (a scientific approach) or as natural science, *Engineering* can be referred to as engineering science or the practice of engineering (Vodolazhskaya et al., 2018). The accuracy of terminology and scientific consensus on the definition of basic concepts is an indispensable condition for setting the goals of education and determining its content.

A comparison of the development of STEM education in China, India, Russia and the United States shows that the fastest pace of this type of education is in US universities, where there are all the conditions for the implementation of this system (Loyalka et al., 2021). Research has shown that in US universities, STEM education influences the formation of critical thinking skills in students; however, in China, India, and Russia, students do not develop critical thinking skills at a sufficient level. At the same time, academic skills are better developed in students from India and Russia. Therefore, it is concluded that STEM programs of education in universities still need improvement and more in-depth study in order to be introduced into the educational space. Researchers from Indonesia, based on the experiment, proved that STEM education is effective in the development of creativity; however, the results showed a low level of development of this skill in students (Sirajudin & Suratno, 2021). Based on these results, it was proposed to introduce a new approach to the study of biology in order to expand the educational process and increase the level of creativity. In the USA, the development of creative and critical thinking skills is included in the curriculum in the context of STEM education programs, so the results of experiments show an increase in the development of these skills by 15-20% after training in STEM education programs (Park et al., 2020). Therefore, such a model of STEM education, as in the USA, can be tested and implemented in the education system of other countries.

The study is based on the assertion by Solomanova (2019) that says that the STEM approach fundamentally changes the traditional view of learning and education. The key 21st century skills – communication, cooperation, critical thinking, creativity – cannot be obtained only in laboratories or from the knowledge of certain mathematical algorithms (Solomanova, 2019). Modern scientific industries that will remain in the future usually require scientists to possess a variety of competencies and areas of interest. Therefore, when training scientists, it is extremely important to go beyond knowledge accumulation while simultaneously discovering and developing additional skills, qualities and interests that scientists need (Höffler et al., 2019). Thus, education is considered as a factor influencing the formation of a new type of professional identity (Martin-Hansen, 2018), which significantly increases the likelihood of future career development in the STEM field.

Foreign researchers emphasize the importance of interaction between education and knowledge-intensive industries in order to improve the quality of education. Tekkumru-Kisa and Stein (2017), examining the scientific and mathematical components of engineering education, note an increase in the readiness of applicants to study engineering and start a career, as well as an increase in the quality of training. At the same time, researchers also report that educational policymakers and seasoned workers are aware of the need to dramatically improve instructional practices in all STEM subjects, in particular in science and mathematics. In the United States, common core state standards for mathematics and the next generation of scientific standards have determined a high-quality curriculum in mathematics and science; however, unfortunately, this vision is fundamentally different from the content of traditional practice in educational institutions (Tekkumru-Kisa & Stein, 2017). As for the problem of developing STEM curricula in Russia, since 2018, NTI competence centers focused on end-to-end technologies have been created at universities, and research and educational programs have been launched in priority technological areas (Kulbyatskaya, 2017).

The assessment of different stakeholders' contribution to education reform, i.e., the influence of stakeholders on this process, is the major focus of interest of modern pedagogical science. While noting the feasibility of involving manufacturing corporations in the educational process, scientists also point out possible risks of large corporations' involvement in STEM education implementation (such involvement is not always viewed as a social benefit and contribution to the development of people). The interest can also be treated as selfish interest; thus, all-round education is replaced by an attractive (in terms of opportunities in the labor market) and relatively simple and quick training of personnel to meet the needs of the companies involved (Vodolazhskaya et al., 2018).

Carlisle and Weaver (2018) believe that STEM centers (Science Education Center, SEC) are of great importance for improving engineering education. According to the researchers, they inform students about the benefits of STEM education and unify the efforts of higher educational institutions increasing their relevance and importance both internally and externally. The centers provide funding, additional resources and incentives for the implementation of STEM education by increasing the number of hours of instructional practices (Evidence-Based Instructional Practices, EBIPs) and STEM research projects, and also contribute to the development of students' skills to create start-ups and implement them in real STEM industries. STEM centers complement such activities with the assessment of learning outcomes and innovations. Today, it is a common fact that STEM SECs have been opened in many US higher educational institutions. Therefore, the increased focus on STEM education at the national level increases the involvement of universities and colleges in education reform towards STEM (Carlisle & Weaver, 2018). The authors believe that the development of available and the creation of new STEM education centers as a result of the interaction of various participants interested in training a new type of workers is an urgent task of the Russian education system.

Conclusion

The modern development of education in Russia and in the world involves the implementation of new approaches to learning based on the renewal of the content of education, which makes it possible to meet the requirements of stakeholders – partners of educational institutions, who are interested, first of all, in the results of professional training of graduates. STEM education is one of these approaches. The approach is defined as flipped learning as practice (inventing and designing devices and mechanisms) comes before theory, which is mastered in the process of performing assignments. The features of STEM education are the active application of the principles of integration and the project-based approach in the educational process. The content can be renewed provided that fundamental scientific disciplines based on modern practical examples and tasks are studied.

The methods, forms, and means that are used in STEM education should be associated with new scientific and practical studies, which show the effectiveness of STEM technologies in practice, as well as increase the professional orientation of training and motivation of graduates to choose a career in STEM industries. Graduates of higher educational institutions used to receive sector-specific training; in contrast, today the labor market imposes new requirements. In the light of developing technology, automation of production and everyday life, specialists who are capable of integration, communication, and teamwork are in demand; they must be aware of the latest trends in science and technology, be confident in their abilities, as well as be able to apply scientific and technical knowledge in real life. STEM education meets all these requirements. The ultimate goal of STEM education is to awaken students' interest in STEM subjects at the beginning of their studies, which will contribute to the competitiveness of graduates when they enter the labor market, and, in turn, will benefit the Russian economy focused on global technological challenges. Thus, effective programs for the implementation of STEM education developed according to the standards of the National Technology Initiative in Russia should be created at the state level; this will allow the country to quickly and effectively solve the problem of successful employment of graduates in STEM industries.

Competing Interests

The authors declare that they have no competing interests.

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