

Developing technical thinking in Engineering students

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Abstract—The authors consider the core of the concept of "technical thinking" and its structure; characterize the specific features of technical thinking (integration, creativeness, efficiency, and reflexivity), which can serve as a tool for diagnosing the effectiveness of technical thinking skills mastered by students during their training; as well as determine the role of technical thinking in the training of engineering specialists. The main methods for developing technical thinking include technical problem solving, project-based activities, role-playing games, case analysis, brainstorming, morphological analysis, focal object method, and TRIZ methods (the theory of inventive problem solving developed by G. Altshuller), etc. The paper presents findings from research into fostering technical thinking skills in engineering students at Russian State Agrarian University – Moscow Timiryazev Agricultural Academy. The authors identify the main challenges to developing technical thinking skills and, taking account of current development trends in engineering education, suggest ways to solve them.

Keywords— *technical thinking, technical creativity, methods of developing technical thinking, engineering education.*

I. INTRODUCTION

Implementing a competence-based approach [1] implies the development of the prescribed professional competences in students. This, in turn, requires particular focus on the parallel development of universal and general professional competences based on important key skills such as the ability to "think effectively, act effectively, relate effectively and accomplish effectively" [2]. For engineers, these skills are a prerequisite for developing a specific professional type of thinking, i.e. technical thinking. The diverse professional activities of an engineer mean that technical thinking remains the most important (and even foundational) professional personality component that is essential for any kind of engineering activity [3].

The state of the country's economy, its technological capacity and, as a result, competitiveness in the global market depends on the quality of engineering personnel training. However, engineering education in Russia still fails to meet modern needs. Studies aimed at improving engineering education in general, or specific aspects of it, are therefore very relevant. A purposeful study of actual and potential ways and means of shaping the technical thinking

of future engineers within higher education is particularly needed.

II. TECHNICAL THINKING AS A BASIS FOR ENGINEERING TRAINING

A. The Core and Structure of Technical Thinking

The professional activities of engineers are focused on designing, constructing and effective functioning of technological means. The word "engineer" comes from the Latin word 'ingenium', meaning ingenious, witty, and inventive.

The main features of engineering activities include:

- technical application (working out technological means and methods, and their practical use in economic production conditions);
- resolving the contradiction between object (nature) and subject (society) in the process of transforming natural objects into social and artificial ones.

Technical thinking is understood as the process of reflecting on production, technical objects, and processes. It is also understood as the use of mental techniques in operating technical images (both statically and dynamically) [4]. A specialist possessing technical thinking skills must operate equally well with a system of technical and technological knowledge presented either in the form of concepts or in the form of images. They must also master the ability to perform various actions using this knowledge. It is equally challenging to combine the conceptual, imaginative and practical components of mental activity.

The structural analysis of technical thinking helps to reveal its specific features. Starting from these, we can characterize the patterns of technical thinking and diagnose the degree, to which they are present in the study process. Such qualities include an integrated approach, creativity, efficiency, and reflexivity.

An integrated approach is manifested when a specialist uses various means to solve technical problems: concepts learnt in theoretical study, images and actions; moreover, s/he is also able to examine the problem from various angles and anticipate possible changes as a result of decisions made

pertaining to the design, technological, economic and other aspects. Ways to develop this quality of technical thinking include a variety of complex tasks which place students in a situation simulating the real activity of engineers and requiring the comparison of several professional positions.

The creativeness of technical thinking is determined by the fact that engineers are often working in situations of uncertainty. In particular, an engineer should be able to identify technical problems; formulate new ideas when considering a situation from a different angle; propose unusual functional applications of a technical object; rationally change the process; and justify the effectiveness of a proposed solution. It is obvious that different fields of engineering activity require a different ratio of the creative and reproductive components of technical thinking. But students should be ready to solve both subject-based creative study tasks and object-based creative technical tasks (rationalization, invention, and research).

It is important to train future engineers to use special thinking techniques for creating new ideas (using heuristic methods). But there is only one way for students to develop creative skills, – and that is by finding solutions to creative problems, including technical contradictions. The purposeful elaboration of a multi-level system of creative tasks is therefore required at all training stages in order to develop the creative component of students' technical thinking. Lecturers should take into account that an educational process devoid of any elements of creativity is damaging to students with high creative capacity. An individual approach to the training of such students should therefore be taken, which includes identifying special creative tasks, as well as involving them in various types of inventive and research work.

The efficiency of technical thinking is determined by the fact that a specialist engaged in real activity has to make decisions in a limited time and under very diverse conditions. In order to practice this quality of technical thinking when studying various subjects, technical problems reflecting real production conditions should be tackled:

- by establishing a time limit for solving the problem, which improves the speed of transition from thinking to actions and vice versa;
- by building uncertainty into source data (setting tasks with excessive, incomplete or partially incorrect data; tasks involving selecting the optimal solution from several options; multi-stage tasks constructed in such a way that solving the first stage specifies the conditions of the second stage); these tasks encourage students to pay attention to the detail of particular situations .

Developing the speed of technical thinking is facilitated by role-playing and competition situations, for which it is advisable to use, among other means, the wide opportunities of information and communication technologies [5; 6].

The reflexivity of technical thinking is an important quality not only of technical thinking, but also of an engineer's personality. A strive for self-improvement, an ability to plan life, as well as psychological readiness for professional activity depend on the formation level of the reflection of a professional. Future engineers, in particular,

should be well aware of the process, ways and results of thinking.

The mental activity reflection of students is usually hidden from teachers, but it can be controlled by teaching them to use questions that express a problem situation. So, the starting-up questions (Who? What?) allow selecting objects from the background. Definitive questions (Where? When? How much? How? For what purpose? etc.) help clarify many properties of the considered object. Causal questions (Why? How are they connected? etc.) make it possible to understand complex relationships and links, identify the causes and effects of an impact on an object. Questions hypotheses (What if ...?) enable us to formulate an assumption. It is very important that teachers introduce students to such a typology of questions and show samples of reasoning through questions.

B. Methods of the development of technical thinking

For the development of technical thinking, a variety of methods are applied that are successfully incorporated into various innovative learning technologies: design-organized, module-based, problem-oriented, contextual learning, etc.

Methods of developing technical thinking can be applied both individually and in the process of collective learning and cognitive activity, the possibilities of which are often increased due to the so-called over-additive effect, when the final result of collective activity far exceeds the sum of the efforts of people working alone.

The universal and one of the most effective methods for the development of technical thinking is *the technical problem solving* that does not make intrusive, or annoying algorithms that require great patience, stimulate students' interest in solving problems, encourage them to active learning and cognitive activity [7; 8].

An important place in the development of technical thinking belong to *the method of projects* – a way of achieving a pedagogical goal through the detailed development of a scientific or practical problem, which should be completed with a very real, concrete, and “tangible” result. The main purpose of the project method is to provide students with an opportunity to independently acquire knowledge in the process of solving practical problems or problems that require the integration of knowledge from various subject areas. This is a tremendous opportunity for the formation of professional competences of future specialists and the development of their creative thinking. Moreover, the project method itself is integrative in nature, combining various study, search, and problem-based methods that are creative by their nature [9]. The teacher in the project plays roles of a developer, a coordinator, an expert, and a consultant.

The “case analysis” method implies analyzing by students grouped into subgroups a real or hypothetical situation and developing criteria for solving problems and an action program. This method also contributes to the introduction of learners to their future professional activities. A situation analysis involves the identification of not so much facts but the indicators of a problem and its factors. A key to problem solving is the self-development of their own assumptions by students. In organizational terms, an important role is played by students acting as “managers”

and “critics” (to whom the teacher confers part of his/her authority). Thus, the distance between the organizer of the study process and the students is minimized, the interaction between the students themselves has a positive effect on the creative nature of problem solving.

The synectics method helps future engineers learn to analyze contradictions (technical, economic, social, etc.), formulate problems, highlight the main goal of the search, use symbolic, personal, or fantastic analogies to solve the problem. At the same time, students develop an ability for synectic thinking: an ability to abstract from the subject of discussion, an ability to switch, move away from obsessive ideas, an ability to listen to others and tolerate their ideas, an ability to find unusual features in ordinary objects and vice versa.

The purpose of *brainstorming* is to put forward as many different ideas as possible. This method allows, by separating the process of generating ideas from their criticism and evaluation, to overcome the inertia of thinking and activate the association-making abilities of a person when solving problems in a group. During a brainstorming session, there is a kind of chain reaction of ideas that leads to an intellectual explosion: 99% of ideas arise like an electric spark coming in contact with other people's thoughts. The method includes the following main stages: preparation, generation of ideas, analysis and evaluation of ideas. To solve a technical, environmental, or economic problem, as a rule, two groups of participants are formed (7–10 people each): “generators of ideas” will offer ideas, and “experts” will be engaged in their analysis. The work of groups is organized by the leader, whose task is to formulate the task, divide the participants into groups, and ensure the fixation of ideas. “Shifting” in time of hypothesizing and evaluating versions allows students to freely discuss the problem and express as many ideas as possible in a relaxed and informal atmosphere. Even if these are, at first glance, unrealistic sentences, the main thing is that students can abstract from the existing stereotypes, believe in their abilities, begin to think outside the box and not to be afraid that their proposals will be categorically rejected or ridiculed.

Morphological analysis refers to the logical methods of finding new ideas and solutions using the construction of so-called morphological tables. Vertically, in the table columns, the highlighted essential signs of a problem or a new object are recorded. Horizontally, in the line of each sign, all possible variants of its manifestation are recorded. Thus, any new object can be created by combining various options for the given parameters. It is clear that not all objects elaborated in this way will work or be interesting, however, there are several algorithms for optimizing tables so that the search for the necessary and effective variant can be fast enough. The purpose of the morphological analysis is to identify and describe all potentially possible solutions to a problem (to make a matrix of possible solutions).

The method of focal objects is a method of associative search for new ideas and characteristics of an object on the basis of attaching the properties of other randomly selected objects to the original object. Transferring to the object under study the properties of other objects that have nothing to do with the original one often gives sound answers, since it

allows looking at the conditions from a different non-obvious view.

A *business role-playing game* is a method of imitating managerial or production decisions carried out according to predetermined rules in artificially modeled situations. Simulation modeling of the real conditions of a specialist's professional activity usually involving one or several problem situations allows to represent professional, social and personal connections in all their diversity. This method is especially effective under the condition of joint activity of students. A teacher here needs thorough preliminary preparation: selection and characterization of roles, determination of participants' responsibilities, interests and tools, identification and modeling of the most characteristic types of professional interaction between “officials”, etc. A well-organized constructive discussion with the maximum participation of all the players is capable of generating truly creative work.

The importance of business role-playing games is difficult to overestimate, since this method not only actively “immerses” participants in their future professional activities, but also contributes to the formation of cognitive and professional internal incentives, as well as skills and abilities of social interaction and communication, creative activity, individual and joint decision making; fostering a responsible attitude to business matters, respect for the social values and collective and social attitudes as a whole.

A well-proven type of game methods known as *the Walt Disney method* aims at developing creativity in the form of a role-playing game, in which participants approach the task from three points of view: creative, realistic and critical [10]. The method can be used both individually and in a group. In the group variant, participants occupy the positions of three roles:

- The Dreamer plays the role of a creative person, an enthusiast who offers diverse, even unreal, solutions to a problem;
- The Realist takes a pragmatic position, suggests ways of structuring and planning the work, and determines the steps needed to solve the problem;
- The Critic tries to assess the value of ideas, finds mistakes in the proposed variants, and identifies weaknesses in the previous proposals.

During the role-playing game, participants can cyclically change their roles and continue discussing the problem until a solution is found.

A similar approach is used by Edward de Bono in *the ‘Six Hats of Thinking’ method*, which is based on correlating the hat colour with separate stages of the creative process: gathering information, generating ideas, analyzing ideas, finding resources for translating ideas, etc.

The theory of inventive problem solving (TRIZ) worked out by G.S. Altshuller in the 1950s is highly promising in terms of developing creative thinking of future engineers. TRIZ includes specific methodological tools for finding new ideas:

- algorithm for inventive problem solving;

- a set of standard solutions to inventive problems;
- typical methods of elimination (resolution) of contradictions;
- methods for the development of creative imagination;
- methods of forecasting the development of technical and other systems.

These methods are significantly different from the trial and error method and all its modifications. Instead of searching blindly, they are built on a system of logical operations, subject to the development laws of technical or economic systems. These systems do not emerge or develop arbitrarily, but according to certain laws that can be used for conscious and purposeful industrial or business problem solving. The process of solving these problems can be viewed as identifying, analyzing and resolving contradictions – such interaction in a system, in which a beneficial action simultaneously causes a harmful one [11; 12]. The effect of the beneficial effect (its enhancement) or the elimination (weakening) of the harmful effect causes deterioration either in separate parts or in the system as a whole. The TRIZ method can be used to form a culture of creative thinking of students as a conscious, purposeful and controlled process of mental activity.

Reflecting the main stages of thinking processes performed by the subject in analyzing problem situations and finding effective solutions, TRIZ is increasingly being used in the system of higher and further education to form a culture of innovative thinking in both students and teachers.

III. STUDY OF THE PROBLEM OF THE DEVELOPMENT OF TECHNICAL THINKING IN ENGINEERING STUDENTS

The study of the pedagogical conditions of the effective formation of technical thinking in the process of holistic professional training of future engineers was carried out on the basis of Russian State Agrarian University – Moscow Timiryazev Agricultural Academy (Institute of Mechanical and Power Engineering named after V.P. Goryachkin).

In the course of the empirical research conducted in 2018, the following tasks were solved:

- 1) to identify the dynamics of the formation level of technical thinking in students in the process of their training;
- 2) to analyze the opinions of lecturers and students about the key points of the formation of technical thinking of future engineers.

When solving the first task, Bennett's standardized test was used to assess the level of technical thinking development (an assessment of the ability to read drawings, understand technical device diagrams, solve simple physical and technical problems). When solving the second problem, use was made of specially designed questionnaires for students and lecturers. The questionnaires were focused on activating the respondents' reflexive processes about the professional development of future engineers.

The empirical study was attended by 618 students (approximately 150 people from different training areas in each study year) and 30 lecturers from various engineering departments with work experience ranging from several

months to 45 years. The results of empirical research are presented in the table.

TABLE I. THE RATIO OF REAL GRADES, SELF-ASSESSMENT GRADES AND LECTURERS' ESTIMATES OF THE LEVEL OF TECHNICAL THINKING OF STUDENTS (A 5-POINT SCALE)

Year	Real assessment of the level of technical thinking	Self-assessment of the level of technical thinking	Lecturers' estimates of the students' level of technical thinking
1 st	3.64	3.38	2.2
2 nd	3.83	3.58	2.8
3 rd	3.47	3.42	3.6
4 th	3.38	3.31	3.8
Average score	3.56	3.47	3.1

As a result of the study, it has been found:

1. The level of technical thinking development of students of all study years in the Institute of Mechanical and Power Engineering is above average.

2. The traditional study process in a technical university contributes to the development of technical thinking, but the dynamics of the process results is unstable.

3. Students' self-assessment of the level of technical thinking does not correspond to the real assessment obtained as a result of testing. The average data on self-assessment of students of all study years is below the average scores of the real assessment.

4. Analysis of lecturers' estimates of the level of technical thinking development of future engineers has shown that the average score of teachers' estimates is lower than the real estimates and self-assessment results of students; lecturers are much less likely to appreciate the technical abilities of 1st and 2nd-year students (as compared with real grades and self-assessment results), but they much more highly appreciate the abilities of 3rd and 4th-year students.

Interesting data were obtained during the analysis of teaching staff and students' questionnaires. The questions were aimed at ascertaining the level of awareness of the technical thinking development while getting higher education. Answering the question "Which academic subjects contribute to the development of technical thinking?", students placed engineering graphics (1), mathematics (2), materials science and construction materials technology (3), physics (4), theoretical mechanics (5), while the lecturers had a different point of view: mathematics (1), theoretical mechanics (2), physics (3), machine parts and designing fundamentals (4), tractors and automobiles (5). It should be noted that students pointed out the utmost importance of engineering graphics, which is quite natural, since it is this subject that forms the compulsory figurative component of technical thinking in the first year of study. However, the lecturers, not realizing the importance of this subject, put it in 9th place.

The lecturers answered the question about the factors that positively and negatively affect the process of technical thinking development in students. As a result of analysis, the

answers were grouped conditionally and different factors were identified – those of “students” (their motivation, abilities, assiduity), “lecturers” (professional and pedagogical competence) and “administration” (material and technical conditions for the implementation of the study process).

The survey results have shown that success in the formation of technical thinking is primarily due to the influence of “student” factors (65.5%), to a much lesser extent the influence of “lecturer” factors (27.4%), and it depends only slightly on the “administration” (7.1%). The reasons for negative learning outcomes according to the lecturers are as follows: “student” factors (40.4%), “lecturer” factors (29.8%), “administration” factors (29.8%). Therefore, according to the lecturers, the students themselves are primarily responsible for the successes and failures in the learning process. But when analyzing negative outcomes, the share of the “student” factors is less than the total share of factors of university representatives (59.6%), i.e. its “internal environment”.

The lecturers offered interesting ideas about their own methods and techniques aimed at the formation of technical thinking in students. Only 20% of the lecturers surveyed indicated the use of the method of creating a problem situation in their work, which is the main tool of developing thinking skills. The conducted empirical research has shown that the formation of the technical thinking of future engineers occurs more spontaneously and is an outcome of the study of technical subjects.

Analysis of student self-assessment of the level of technical thinking development has shown that it is not adequate. By the average scores calculated by the training course outcomes, self-assessment is lower than the real score. Appealing to individual data shows that students with low test scores tend to overestimate themselves, while students with high test scores tend to underestimate themselves. But only the adequate self-esteem is an effective regulator of behavior. Therefore, students find it difficult to analyze changes in their own personality, which can be considered as one of the reasons for the insufficient development of the technical thinking in future engineers.

The lecturers poorly represent the algorithm of a specialist’s formation and his/her most professionally important traits (in particular, technical thinking). In their view, the dynamics of the development level of technical thinking in students (from the 1st to the 4th year) has a pronounced linear character, which can be explained by the existence of conscious and stable stereotypical ideas about the significance of higher education for the development of thinking skills. Lecturers tend to explain their success and failures as caused mainly by the students’ audience and its characteristics, without attaching much importance to improving their own professional skills. In their opinion, the development of technical thinking is more explicitly observed in senior years when special subjects are typically studied. They underestimate the importance of preparing for higher education and career guidance training in junior undergraduate years when basic intellectual development takes place.

In this regard, the need to improve the skills of lecturers to use innovative training technologies in engineering education should be emphasized as the first and foremost

important condition for the effective development of technical thinking in future engineers [13; 14].

IV. CONCLUSION

As the research results show, improper focus of training and non-systematic development of technical thinking throughout the entire study period of future engineers can cause only random, unstable and poorly controlled changes in the level of technical thinking in students [15; 16].

The development of technical thinking of future engineers will be most effective if it is carried out systematically at all stages of an engineer’s professional growth (including career guidance work with schoolchildren and their familiarization with engineering professions, the system of professional, further and supplementary education). Efficient implementation of this task also requires that the university and faculty members, students, and perspective employers should joint their efforts. The key condition for solving the problem of improving the training quality of future engineers is to enhance the psychological and pedagogical qualification of lecturers in compliance with redesigned and modified curricula.

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