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# Technoinnovation as an essential element of training for engineers

**M V Solodikhina[1,2] and A A Solodikhina[3]**

[1]Moscow Pedagogical State University, 119991, 1/1 M. Pirogovskaya Str., Moscow, RF
[2]Peoples' Friendship University of Russia, 117198, 6 Miklukho-Maklaya Str., Moscow, RF
[3]National Research University Higher School of Economics, 109028, 11 Pokrovsky Boulevard, Moscow, RF

E-mail: asolodikhina@hse.ru

**Abstract**. The paradox of the modern labor market, when there is a shortage of engineering and technical personnel in the presence of a sufficient number of graduates of technical universities, is associated with a deformation of demand: only those specialists are in demand, which are either economically unprofitable or impossible to replace with technical devices, since so far artificial intelligence is not capable of creative creating innovations. The problem is that there are disproportionately few well-prepared schoolchildren among applicants to technical universities, and among university graduates there are many who have chosen a career outside the STEM sphere. There is no shortage of engineers, there is a shortage of highly qualified creative specialists. To train such specialists, it is necessary to increase the inflow of the most talented and creative students to technical universities, and then keep them in the STEM sphere. To test the hypothesis that a good way of attracting young people to the choice of an engineering career is to endow students with successful experience of technological invention, courses “Techno-Startup” for schoolchildren and “Technoinnovation” for students of technical universities were developed. The objectives of these courses are: to give students the experience of creating techno-innovation, to increase the motivation for a career in STEM among the most prepared students, to form critical thinking.

## 1. Introduction

The strategy for the development of engineering and technical education in many countries of the world is based on the idea of the growing shortage of specialists in the STEM field [1]. But not everyone agrees with the problem of a shortage of engineers [2], believing that there is rather an unsatisfied demand for certain specialties or in certain regions [3]. But, perhaps, the main reason that, despite the presence of a considerable number of graduates in the STEM field, the economy desperately lacks these specialists, lies in the discrepancy between the preparation of the bulk of graduates and the needs of industry and business. In accordance with the Autor curve [4], specialists of average qualification are less and less needed - their functions can be algorithmized, and they are gradually replaced by technical devices (for example, many calculations, calculation and drawing of drawings are performed automatically). Either workers whose activities are economically unprofitable to automate, or specialists of the highest level, capable of creativity, innovation - that is, those that are not subject to programming and which are not yet capable of replacing artificial intelligence, are in demand. The vacancies of the first category of workers do not correspond to the salary expectations of university graduates, and the system of higher engineering and technical education does not yet supply highly qualified specialists with experience of innovation and, most importantly, possessing critical thinking [5], in the amount necessary for the country's innovative development.

In the United States, allegations of an insufficient number of STEM specialists have led to the popularity among politicians and business of the STEM pipeline concept [5], based on the idea that the problem of engineering personnel can be solved by an overall increase in the number of graduates in the field of science and engineering (S&E) by attracting schoolchildren, including those who previously rarely associated their careers with S&E (women, minorities), and in every possible way retain these students until the completion of their academic program. The strategy showed low efficiency (80% of minorities and women either did not graduate from college or after graduation chose a career not related to STEM [6]). Similar ideas in Russia - to increase the number of budget-funded places in engineering and technical specialties and strive to keep all students in the university until graduation - also work not in the best way. The availability of higher technical education, coupled with the low interest of young people in the career of an engineer (a global problem identified in many studies [7, 8]) led to negative selection: although the leaders in the quality of admission are scientific and engineering universities (MIPT, MEPhI, ITMO University), on average, applicants with mediocre scores enter engineering specialties [9], which prevents them from mastering the university program at the proper level. By the end of the training, half of the students begin to regret their choice [10]. As a result, only 68% of graduates with a diploma in the field of "Engineering, technology and technical sciences" and 66.3% in the field of "Mathematical and natural sciences" work in the specialty [11]. Of course, the influx of young engineers is beneficial for other sectors of the economy. For example, in 2010, 5.4 million people worked in STEM in the US. And 16.5 million Americans, "including many in non-STEM jobs, such as sales, marketing and management-reported that their job required at least a bachelor's degree level of S&E expertise" [12]. But the problem of the lack of highly skilled creative engineers is not being solved.

Perhaps the concept of the STEM pipeline will turn out to be effective if the focus is shifted - firstly, to focus not on the number of students involved in technical universities, but on their quality, that is, to reverse the trend when the most prepared students refuse to connect their lives with S&E [13] , secondly, to combat the leakage of the most talented students from the profession by involving them in productive engineering activities, increasing the motivation to work in the S&E field and giving them the experience so valued by employers, and, thirdly, to shift the emphasis in learning from the reproductive transfer of knowledge to students to developing their skills of independent search, assessment, awareness and application of knowledge in the course of practical activities, that is, the formation of self-study skills based on the development of critical thinking, which is extremely important for an engineer in a rapidly changing world. The main question is how to achieve this?

The unattractiveness of an engineer career for young people is due to the fact that, firstly, it is not perceived as creative, and for modern youth it is important to have the opportunity for creative self-expression, and secondly, the idea of its significantly lower prestige and a lower level of salaries has not been eliminated in society than, for example, in economic professions, which is confirmed by the data of paid admission to universities [9].

In fact, the word "engineer" comes from lat. root ingeniare, which means "create", "create", "implement", and the career of an engineer provides great opportunities for creative self-expression, for creating technical devices based on scientific knowledge that transform the world around them and provoke new scientific discoveries (which is observed in recent 1.5 century). At the same time, engineering and economics are inextricably linked - it is no coincidence that most industrial companies and corporations were created and initially led by techno-inventors who were able to realize themselves in business. But now economic and technical education is divided and opposed - in schools there are engineering and economic classes, in technical universities, economic disciplines are mostly studied formally. Perhaps if you bring this understanding of engineering to schoolchildren, show that technoinvention can be learned and is an exciting creative activity, then students can take a fresh look at S&E. And gaining successful experience in the field of S&E (for example, developing a technical device and preparing it for implementation) can attract the most talented students to technical universities [14], and keep students in S&E careers, since “Based on expectancy-value theory persons pursue a career in those subjects in which they are most competent ”[15]. To test this hypothesis, the courses “Techno-Startup” for schoolchildren and “Technoinnovation” for students of technical universities were developed.

But there is proviso. In technical universities, in order to familiarize students with the profession of an engineer, there is an industrial practice. But in the form in which it is present in most cases, it is of little use for increasing the motivation of students to stay in the S&E sphere: almost 40% believe that their industrial practice was formal and gave them almost nothing in terms of their future profession [16].

## 2. The principles of building the courses "Techno-Startup" and "Technoinnovation"

Educational leaders, educators and researchers from different countries consider the project-based approach to be one of the main innovative ways of teaching S&E [17, 18]. In Russia, a course has also been taken to expand the practice of mass project education in secondary and higher education. But so far, in the overwhelming majority of cases, the result of an educational project is not a unique material or intellectual product, but an abstract. On those rare occasions when students create something new, there are usually no attempts to commercialize the product of the project. But the innovation itself (invention), no matter how useful and unique it is, has little effect on the development of society until it receives the prefix "in-" and becomes an innovation, that is, it goes the way of commercialization and implementation, be it a mass market or industrial production. A project created for the sake of the project itself brings a student much less close to the desire to be an engineer than a project that has been introduced into production, albeit the smallest one.

Therefore, both courses were based on project activities, the result of which should be an objectively new or significantly improved product (model, MVP, prototype) that went through the full innovation life cycle from the problem to preparation for implementation and the development of a diffusion strategy. The main educational goal of the courses is the development of students' critical thinking as future innovators [19].

The basic principles of building courses are presented below.

1. Design is based on the problem, and not vice versa. The problem must be important for society or some part of it, which presupposes its successful commercialization. Sometimes a problem is posed by an external customer or the terms of a competition in which students plan to participate. But more often students themselves determine the problem that they would like to solve by developing a new technical device, and this is one of the most difficult stages in training [20, 21]. Here, when teaching, it is important to show the largest possible number of problem situations that a person encounters on a daily basis, which have been successfully resolved and brought commercial success to developers (from the simplest ones - for example, a snow blower for porches, a coffee cup holder for bicycles, to complex ones - for example, traps debris in water bodies).

2. Special care for the formation of the project team, because, on the one hand, a technological project involves the separation of activities (programming, design, development of technical documentation, selection and search for materials, etc.), and on the other hand, it is necessary to avoid “the Ringelmann effect”, when as the team grows, the productivity of each team member decreases.

3. Emphasis on the development of students' thinking as the main educational goal of project activities. At the stage of invention, the formation of design thinking is taking place, at the stage of entrepreneurship - business thinking.

4. Competition: At the end of the training, startups are evaluated by a competition committee consisting of S&E entrepreneurs and potential employers. “Project through contest had the greatest impact of development on the theoretical knowledge of engineering design, and the skills, experiences and abilities to use technologies, and the power of teamwork to make decisions” [22].

The development of a project in the courses "Techno-Startup" and "Technoinnovation" goes through a number of stages.

After the problem is posed, there is a stage of empathy, at which the project team must answer the question "who and how does the problem affect?" To do this, it is necessary to dive into the problem area, determine the potential consumers of the project product, the relevance of the problem for them, as well as find various existing solutions and determine the reasons for their non-optimal. Based on this research, the project team estimates the potential relevance of the project product and its characteristics.

In Russian educational projects, the empathy stage is usually skipped, and the forecast of the demand for the created devices or technologies on the market is not made. It turns out an invention for the sake of an invention without commercial potential.

At the “focusing” stage, an inventive problem is formulated - that is, the project team answers the question of what it is going to create. For this, students are trained in the TRIZ methodology (the theory of inventive problem solving developed by Altshuller) as part of the course, so that they can translate the problem into the formulation of a technical task.

The central stage of invention is the generation of the maximum number of ideas (any, even those that seem absurd), followed by a brainstorm in the project group. To do this, students get acquainted with the methodology of generating ideas: the strategy of W. Disney, the technique of colored hats by de Bono, trendwatching, which allows them to look at the problem from an unusual perspective, see non-standard approaches, and find non-trivial ideas for solving the problem. Students first generate ideas individually, independently of each other, so as not to follow in the mainstream of other people's thoughts, but to fantasize themselves. It is only when everyone has their own pool of independent ideas that project team members exchange them, rethink each other's ideas, and create “second generation ideas”.

The stage of choosing the only idea to be implemented requires experiments or inviting experts to assess the pragmatism and uniqueness of each idea, to determine the optimal way to achieve the most rational of them.

The inventive stage is completed by the stages of creating and testing the minimum viable product (MVP). Here it is important to determine what intermediate and final checks need to be carried out in order to understand the feasibility of the idea, its prospects, and the necessary improvements. Prior to the MVP testing phase, the project team selects materials for the prototype and estimates the cost of the final product, the duration of the full cycle of product creation, and cost justification.

The laboratory base for design activities is usually provided by an educational institution, but it cannot always finance the component materials for the prototype. In this case, students independently seek funding from external sources. Such sources are grants, crowdfunding, specialized exhibitions and conferences, where it is possible to find sponsors and partners who are ready to provide equipment or components in exchange for advertising, holding events for employees and their children (for example, entertaining lectures with demonstration of robots), testing their products (for example, a company that manufactures car video recorders handed over an analog video camera to students developing underwater robots at the educational and scientific youth center "Hydronautics" of the Bauman Moscow State Technical University, and they tested it on their underwater equipment at different depths). If the prototype has successfully passed the tests and its characteristics correspond to the characteristics determined at the empathy stage, then you can prepare a presentation of the product (to the customer, for a competition, for patenting, publication, etc.) and start a startup. The stage of presentation and public approval of the results obtained is extremely important: interest-enjoyment values and attainment values are most important to students' motivation to participate in technology and design activities [23]. The Technoinnovation course helps students to find their own model for the successful commercialization of the project product, to orient those who want to open their own startup in the current grant and competition programs. The course forms a knowledge and practice base that facilitates the first steps in the field of high-tech business based on the created project, gain experience of victories and mistakes.

Of course, the level of projects of pupils and students differs significantly. Technical universities provide their students with a solid technical background that allows them, with the proper approach and desire, to design high-tech devices, but almost no experience in creating innovations, launching startups. And studying in the format of "pushing knowledge into the learner" of many leads to demotivation and leaving the profession. Therefore, from the point of view of motivation, schoolchildren and students are in the same position - both of them need to be given the joy of creation, creativity and the usefulness of their activities.

The above principles of organizing the Techno-Startup course were tested twice in a remote format for Russian schoolchildren (with international participation): once at the Medeleev Center Technopark (76 people), and the second time at the HSE Lyceum (58 person). The Techno-Startup course is aimed primarily at students aged 14-15. It is at this age that it is important for schoolchildren to show the career and creative potential of the STEM sphere, since it is at this age, according to studies [24], that they determine their choice of profession. The training course "Technoinnovation" was carried out by 123 students of engineering and technical areas of training.

32 students were trained and worked as trackers of project teams. The tracker is a mentor who helps teams through a special tracking methodology, the main tool of which is asking the right questions to the team, directing students in the right direction, suggesting where and how to find the necessary information and funding, linking with experts, etc.

## 3. Discussing the results

Since the main goals of the courses were: 1) to give students the experience of creating a techno-innovation, 2) to increase the motivation for a career in STEM among the most prepared students, 2) to form critical thinking, then the assessment of the success of the courses was based on these parameters. In both courses, 100% of project teams created MVPs, of which almost 36% reached an industrial prototype, a third of the teams made their first sales (the overwhelming majority are students, not schoolchildren). The university students launched four startups, three of which received grants as a result of victories in contests and hackathons. 54% of students in grades 10-11 (the course was also studied by schoolchildren of grades 8-9) presented their projects at the Olympiads with a project component from the "List of Olympiads for Schoolchildren", the prizes in which allow them to receive benefits when entering universities. Taking into account the fact that all projects have been created in the field of science and technology, schoolchildren expect to receive benefits for admission to technical universities or applied physics. Taking into account the rules of the Olympiads, these students are confident in their high USE scores in STEM subjects, that is, they are well-prepared applicants.

All students of the courses twice passed diagnostic surveys, which contained motivational questions, questions for natural science, engineering and financial literacy, questions for assessing critical thinking (with an emphasis on rational, creative and analytical components) [19].

The results showed that during the training there were positive changes in all three main motives for choosing a profession: 1) after the courses, the perception of the prestige of STEM professions increased by an average of 2.4 points out of 10; 2) the perception of the possibility of achieving material well-being for those who chose the career of an engineer increased by 1.8 points out of 10; 3) the attractiveness of the engineering profession as personally interesting, creative, contributing to self-development and unlocking potential for students with an average score exceeding 4.5 and 2.5 points for students with an average score lower by 4.8 points (almost 2 times) 4.5. At the same time, some schoolchildren said that they previously planned to receive a purely economic education, and now they are thinking about getting a basic engineering education, and then an MBA degree.

The experience of creating techno-innovation deepened and expanded natural science and engineering knowledge, translated them into a practical plane. Financial literacy, initially rather low, improved significantly in a narrow corridor of functions that were directly related to the completion of the course assignments. When analyzing changes in the components of critical thinking, the greatest shifts were noted in creative thinking (for example, in the ascertaining survey, students, on average, offered 0.8 ideas for solving a problem-situational task, and in the control survey, 3.3 ideas each). Expert trackers' observations of students confirmed the changes recorded in the quiz.

Thus, the introduction of the Techno-Startup course for schoolchildren at engineering universities is one of the most effective ways of career guidance and preparation for entering universities. At the same time, the share of well-trained applicants is significantly increasing. The introduction of the TechnoInnovation course increases the motivation of students for a career in STEM, provides an experience of innovation and develops critical thinking, especially its creative component. That is, it allows in the future to increase the output of engineers who are becoming more and more in demand in accordance with the Autor curve.

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