Education and Information Technologies (2022) 27:2569–2584
https://doi.org/10.1007/s10639-021-10709-7

Developing an innovator's thinking in engineering education

Anna Solodikhina[1] · **Maria Solodikhina**[2,3]

Received: 22 February 2021 / Accepted: 10 August 2021 / Published online: 27 August 2021

Abstract

Engineering education must be changed following the change in the labor market. The cult of innovation has led to a demand for innovators who have both the mindset of an inventor who can see a problem and find a way to solve it, and the mindset of an entrepreneur who is ready to bring that solution to life. Thus, teaching a techno-innovator involves combining STEM education and business education with a common goal to develop the innovator's thinking as a symbiosis of design thinking and business thinking. The tool for the formation of design thinking can be the link of "STEM cases + project", and the tool for the development of business thinking "entrepreneurial cases + startup", a startup as the inculcation and diffusion of the project product. Cases contain potential problem situations during the development of a techno startup and a chain of tasks that help to see different ways to solve a problem and choose the best one. The assignments are formulated in such way to serve as a trainer for the development of components of design- thinking and business- thinking. The study involved 392 students. The trainees in the system of "cases + startup" showed progress in the development of design and business thinking components and a change in the type of motivation from internal to external, as well as the prevalence of success motivation, which was reflected both at the level of startups projects and the desire to continue working on creating technological innovation.

Keywords innovator's thinking · Technoinnovation · STEM cases · Entrepreneurial cases · Projects · Engineering education

✉ Anna Solodikhina
asolodikhina@hse.ru; solodi@inbox.ru

Extended author information available on the last page of the article

1 Introduction

The labor market in the field of engineering and technology is gradually deformed in accordance with the Autor's curve (Autor, 2019): on the one hand, the demand for workers performing routine manual and routine cognitive labor (labor that can be automated and transferred to technical devices) decreases, on the other hand, there is a growing demand for low-skilled employees (whose activities are economically unprofitable to automate) and highly qualified employees capable of creative creation and implementation of innovations (activities that cannot be algorithmized and automated due to the peculiarities of the thinking process at the "birth of discoveries" (Chernigovskaya, 2016)).

Both quantitative and qualitative growth of innovative activity is observed in the world. Society readily and quickly accepts innovations; a stable "cult of novelty" was formed. An innovation multiplier mechanism arose - innovations generate demand, and demand pushes to the creation of innovations. If earlier inventors were talented nuggets and made up a small part of society, then in the future everyone must become an innovator (Rizvi et al., 2012) to take their place on the Autor curve (Autor, 2019) and compete with artificial intelligence, which is second only to people in empathy and creativity (invention).

Accordingly, the system of engineering education, focused today, should prepare highly qualified specialists who are able to adapt to changes in technology, technologies, the emergence of new knowledge, that is, to be ready to perform "work that does not yet exist, using tools that have not yet been invented".[1] A future-oriented engineering education system should prepare engineers capable of creating new tools, technologies and knowledge. Moreover, it is important not only to make an invention, but also to implement it, that is, to make it an innovation.

In China, it is believed that "universities are cradles for intellectual and technical innovators, and thus building an innovation and entrepreneurship education ecosystem in universities is of strategic importance for national development" (Zhu, 2020), therefore, therefore students receive special training to innovate in the future.

The question is how to build innovation training in engineering education.

2 Training base for innovation

The most obvious solution is to introduce entrepreneurship disciplines into the curriculum of an engineering university. For example, In Institute Cluster IMA (Aachen University) The extracurricular seminar 'How to become

[1] Interview with Ronald Crutcher (Richmond University), *Education Issues*. 2015. No. 4, pp. 21–32. https://doi.org/10.17323/1814-9545-2015-4-21-3

an entrepreneur' provides students with skills they need to generate ideas, setting up a business plan and launch their business (Plumanns et al., 2019).

The example of Russia shows that this approach does not always work. Even with a good system of higher engineering education (in terms of the number of graduates in science and technology, the level of education, research and development (R&D), Russia occupies a worthy position in the Bloomberg Innovation Index and Global Innovation Index) and the presence in the curriculum disciplines related to patenting and entrepreneurship, a country may have fewer inventors and even fewer innovators. In terms of the number of patent applications to its patent offices, Russia lags behind the leading countries by an average of 6–15 times, and uses no more than 2–5% of these patents[2] Moreover, the "gap" between the invested material and mental efforts and the final number of innovative products is increasing (Shick & Sharova, 2019).

One of the reasons that the Russian education system does not "release" innovators is associated with the constantly growing role of various procedures for testing students' knowledge. In the Critical Thinking Foundation,[3] the model of learning for the sake of exams is called the "robin mother" model: the student "swallows" ready-made intellectual food without acquiring the skills of independent search, "extraction" and assessment, which negatively affects the development of thinking. The second reason is the desire of the leaders of Russian education to replace "the system that remained from the Soviet times that tries to train a person-creator with a system aimed at forming a consumer who can correctly use technologies developed by others".[4] Thus now, even in project activities, teachers often require from the student only correctly completed abstracts and demonstration of memorized material, and not the development of something new or improved (Nemolochnov & Solodikhina, 2016). As a result, contrary to international experience, the level of critical thinking of Russian students "is negatively related to student project activity and presentations" (Koreshnikova, 2019, p. 92). Thus, the new Russian education system forms a certain system of knowledge among students, but it has lost the tools that develop thinking and creativity.

But by the beginning of the twenty-first century, thinking "is becoming a key focus of research and policy in higher education" (Szenes et al., 2015, p.574). Respectively, "undergraduate engineering curricula should equip alumni with the thinking skills required for facing current and future challenges, even in favor of content knowledge" (Crawley et al., 2020).

A large number of studies are devoted to the development of engineering thinking (Sharunova et al., 2020)). But the engineer of the future, in addition to engineering, must have both creative and entrepreneurial thinking. In the leading countries of the innovative ratings attempts are being made to build a dynamic thinking process

[2] According to the federal portal PROTOWN.RU http://protown.ru/information/hide/4450.html

[3] The Foundation for Critical Thinking. Available from: http://www.criticalthinking.org/

[4] The speech of the Minister of Education A. Fursenko at the Seliger forum, 2007

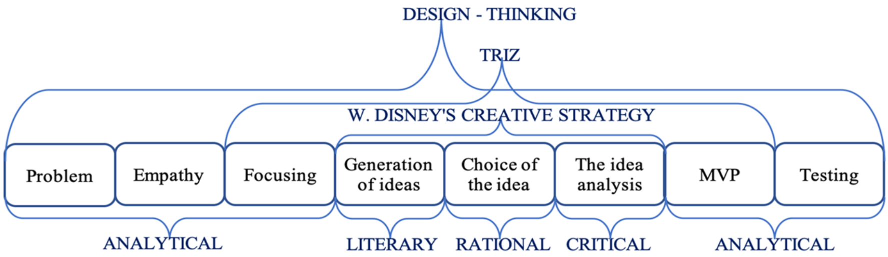

Fig. 1 Leading types of thinking at the stages of creating an invention

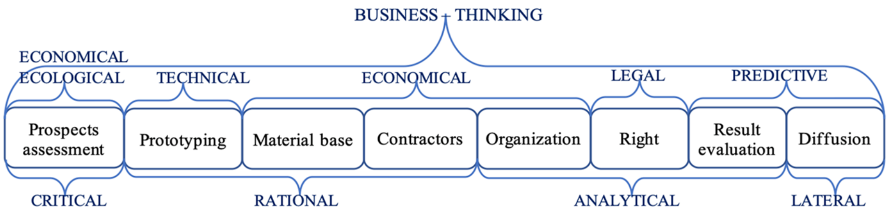

Fig. 2 Components of business thinking at the stage of inculcation and diffusion of the invention

model for high-tech new material product development and new business development (Hayashida & Katayama-Yoshida, 2012).

Similar models are already being applied in education in experimental mode. For example, in 2016, in School of Engineering MIT chartered the New Engineering Education Transformation (NEET), aimed at developing students NEET Ways of Thinking: "cognitive approaches that help students think, plan, and learn more effectively and efficiently on their own and within teams" (Crawley et al., 2018). But this is a separate program that is attended by a limited number of listeners (28 in 2017, 52 in 2018 and 83 in 2019) (Crawley et al., 2020). If you set a goal to increase the number of innovators, then you need to look for other, more massive solutions.

At the National Research University Higher School of Economics (HSE) Department of Innovation Management, an innovator's thinking model has been developed, which consists of design thinking and business thinking, the components of which are analytical, lateral, rational and critical thinking (Figs. 1 and 2). In accordance with this model, the thinking of an innovator is formed in two stages.

Discoveries (inventions) come only to a prepared mind, therefore, the first basis of thinking of an innovator is fundamental STEM education (Science + Technology + Engineering + Mathematics), basic knowledge in their specialty, the basics of management, marketing and business communications, which students study as part of engineering education programs. It is skills, and attitudes necessary to become successful young engineers.

The second basis of the innovator's thinking is critical thinking Research shows that graduate education has limited impact on the development of critical thinking in graduates (Reed, 1998). Critical thinking also needs to be taught. Many universities in the world have corresponding special courses. But critical thinking can also be successfully formed in the study of academic disciplines in their context (Nygren et al., 2018, p.57), especially on the content of integrated natural science courses, which are studied by students of almost all engineering and technical universities in Russia. To do this, it is necessary to adjust the teaching methodology with an emphasis on the development of meta-knowledge (knowledge of how to acquire knowledge), and use tasks that teach students to study the material in accordance with the scientific way of understanding the world, which implies the ability to generalize, simulate, draw analogies, analyze, establish causal relationships. It is convenient to use natural science cases as such tasks (Solodikhina et al., 2019).

Thus, at the first stage, the thinking of innovator base is formed - the necessary system of knowledge and critical thinking by correcting the teaching methods of existing disciplines and introducing new types of tasks.

At the second stage, the purposeful formation of thinking of innovator is carried out as a result of the implementation of the special course “Technoinnovation”, which has interdisciplinary connections with other disciplines. Based on the analysis, discussions and discussions, the design of the curriculum was created, which was based on a cognitive approach (thinking of an innovator), the components of which are formed theoretically using cases and empirically using the implementation of a project that turns into a startup.

In addition to the special course for students, a propaedeutic course was developed for high school students “Techno-Startup” who would like to become innovators and plan to enter engineering universities.

This study analyzed the results of an experiment to test the pilot project of the special course “Technoinnovation” in the 2019–2020 academic year at the HSE undergraduate program and the results of an experiment to implement two streams of schoolchildren, one of whom studied the “Techno-Startup” course in spring and summer in 2020, and the second course - in autumn and winter 2020.

The creation of these courses was based on our answer to the question.

What should be the thinking of an innovator in the context of engineering education and what components should it consist of?

3 Components of thinking of innovator

Technological innovation is inconceivable without thorough engineering and scientific training. Developing an innovator’s mindset requires combining STEM education as the foundation of technoinvention, and business education as the foundation of entrepreneurship. The main focus should be on the development of students’ thinking. “Thinking of an innovator” can be considered as a special kind of thinking, which is manifested most clearly in innovative activity, “serving” this activity and ensuring its effectiveness. It is most logical to form this type of thinking in students of technical training areas, since they have already studied science, engineering, technology and mathematics - the disciplines that are the basis of STEM education, and also studied some of the disciplines related to business education. In this study, STEM education is understood as the integration of disciplines and skills in the STEM area with an emphasis on solving real-world interdisciplinary problems, since STEM education focuses on hands-on activity (Yıldırım & Sevi, 2016).

The creation of a techno-innovation has two stages: the generation of innovation (invention) and its implementation and promotion (entrepreneurship). The strategy of design thinking covers all the stages of the first step most fully. The top of Fig. 1 shows its comparison with the strategy of W. Disney and TRIZ (Theory of Inventive Problem Solving, developed by Altshuller), and the second – business-thinking (Fig. 2 shows the stages of implementation and promotion or diffusion of innovations).

Design-thinking is based on the ability to notice problems or imperfections in the surrounding world (stage “problem” in Fig. 1), assess who and how they affect, dive into a problem area (stage “empathy”), comprehend their scientific and technical essence according to the TRIZ methodology to cut off unpromising solutions, reveal contradictions and find methods of overcoming them (“focusing” stage). These stages are related to analytics.

Therefore, the first important task of the Technoinnovation course is to teach students to detect problems in the world around them that can potentially be eliminated with the help of some new technical device or technology. And then these problems should be assessed - whether the solution to this problem is really important for society as a whole or any category of citizens, or not.

In the Russian system of teaching research activities, the empathy stage is in most cases skipped, in student R&D the needs of consumers are usually not studied, the forecast of the demand for devices or technologies being developed on the market is not built. Most student R&D is done for the sake of evaluation, and if an invention is sometimes obtained, it is not intended to be implemented, that is, an invention for the sake of invention. Students get used to this model. Therefore, in Russia the push model of innovation transfer prevails, where the first stage of innovation is the innovation itself. In countries leading innovation ratings, a pull system is mainly used, when R&D is preceded by an analysis of the market and consumer needs. Therefore, this stage in the course Technoinnovation should be given special attention.

When the problem is found, defined and the usefulness of its solution is revealed, it is necessary to proceed to the stage of “idea generation” of the problem solution. When searching for a solution to a problem, the main role is no longer played by analytical, but creative or lateral thinking. It is this stage that is not yet available to artificial intelligence, so engineers who are able to generate non-standard ideas will be in demand for a long time. Therefore, the disclosure of creative potential and techniques for the development of lateral thinking are very important in the discipline Technoinnovation.

Lateral thinking allows you to perceive objects and processes in unusual combinations, from a non-standard side, to generate non-trivial ideas for solving a problem. Utopian and breakthrough ideas are inherent in lateral thinking. The process of free flight of fantasy should not be limited by rational considerations. Learning based on the reproduction of the acquired knowledge forms the student’s habit of looking for the only “right” solution. In inventing successful strategies, it is the generation of the maximum number of ideas, even those that seem absurd, as opposed to the “cognitive curmudgeon” strategy (De Bono, 1992), followed by a brainstorm

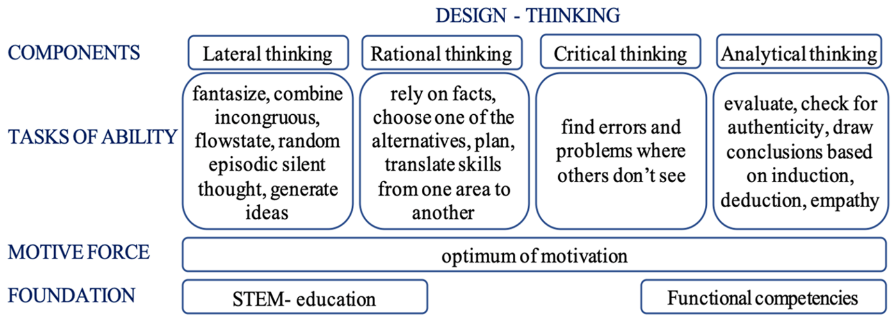

Fig. 3 Chart of design – thinking

in a small group. When the pool of ideas is formed, lateral thinking is replaced by rational thinking, which is responsible for assessing the pragmatism of each idea and determining the optimal way to achieve the most rational of them, without taking into account the difficulties and obstacles. The strategy of isolating and alternately "switching on" different types of thinking when creating an innovation is not new - it was used by W. Disney and de Bono in the technique of colored hats. Difficulties and obstacles in the materialization of an idea are calculated at the stage of "critical analysis". The predictive function of critical thinking (critical not as a synonym for higher-order thinking, but as the cognitive ability to see difficulties, flaws and errors, to question information), relies on STEM knowledge and allows you to test an idea, look for constructive ways to eliminate and overcome difficulties, avoid errors, to anticipate the technical parameters of the functioning of the innovation, its impact on the environment and society during exploitation.

The Minimum Viable Product (MVP) creation and testing phases complete the Invention phase and relate to the analytical component of design-thinking. Thus, design thinking has 4 main components (Fig. 3): thinking analytical, rational, lateral and critical. Design-thinking offers an anthropocentric way to innovate, which has made this strategy popular and promoted, especially by IDEO and the Stanford University-based d.school. But it is discredited by its positioning as a panacea, the development of which promises to make a person capable of creating any innovations regardless of education (Kolko, 2018). This approach does not work in techno-innovation: for design-thinking to become an effective tool for inventive activity, it must rely on STEM education.

The second important component of an innovator's mindset besides design thinking is business thinking.

At the stage of entrepreneurship (Fig. 2), business-thinking provides three types of activities: management, marketing and communication as the establishment of effective partnerships, and consists of analytical, rational, critical and lateral thinking. But the knowledge-competence basis is different. In business-thinking, the presence of such functional literacy as financial and economic, socio-legal, environmental are so important that we can talk about the economic, legal, environmental, technical and predictive components of thinking. These literacies are formed in the study of economic disciplines, law and patent science. But for a person who has

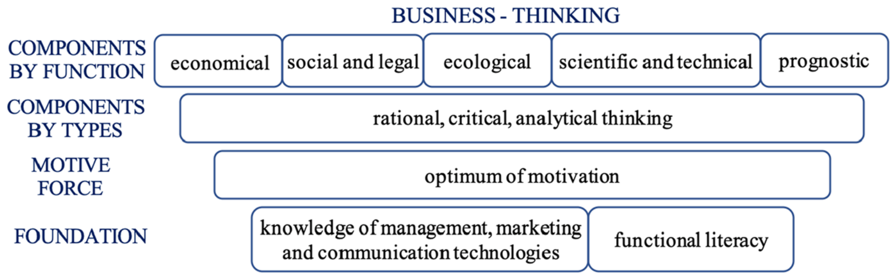

Fig. 4 Chart of business – thinking

chosen and is receiving an engineering education, in order to engage in the implementation of technical innovations, entrepreneurial literacy is not enough. Whether a person tries to innovate is determined by motivation. Therefore, the motive force behind technological innovation is the internal positive motivation for inventive activity in the field of engineering and technology, and the desire to commercialize their inventions. In Figs. 3 and 4 indicate the term "optimum motivation" based on the fact that innovation and entrepreneurship, as complex tasks, based on the Yerkes-Dodson law, high motivation is contraindicated, and innovation itself cannot always lead to the desired motivational results (Devloo et al., 2016).

4 Methodology of formation thinking of innovator

"Student-learning outcomes vary in areas, including academic learning achievement, motivation, and thinking skills" (Wahono et al., 2020). Let's first consider ways of teaching thinking. The most popular model for teaching design-thinking is project development (Dynn et al., 2006; Kumar et al., 2020). But the project activity must have peculiarities. Firstly, the result of project activities should be a material or intellectual product that has a certain degree of novelty. In Russia, unfortunately, it is not always the case. For example, most of the course (non-diploma) projects of Russian students are in reality abstracts: the study of 164 projects created by 36 students during their master's studies "Contemporary Natural Science" at Moscow Pedagogical State University showed that products possessing any the degree of novelty (new or improved devices, computer programs, training models, algorithms, conclusions of scientific significance, etc.) were created only when 17% of the work was completed. This trend comes from secondary education: a study (Nemolochnov & Solodikhina, 2016) shows that the overwhelming majority of school projects, even those submitted to All-Russian competitions, are abstracts. In addition, when defending projects, teachers are usually satisfied with the student's demonstration of the skills in applying subject knowledge and rarely require students to the serious analyze the presented materials and to predict possible trends. With this approach, project development does not contribute to the development of thinking skills.

Secondly, educational project activity, in contrast to innovation, is not aimed at product introduction and commercial success. To form thinking of innovator it is necessary to introduce the stages of empathy, product economics into project activities (choosing a monetization model, drawing up a financial model, calculating Unit-economy and Cash Flow, break-even points), creating an MVP and testing it (a prototype can have a high cost, therefore, to check the relevance of requirements of the target audience and the willingness to pay for a product / service first create an MVP). In this form, project activities become the basis for the formation of thinking of innovator (Solodikhina, 2019).

Thirdly, the project activities of students and their tutors must be taught. For technological innovation, it is important to know the strategy of design-thinking, the techniques of TRIZ and abduction. It is most effective to use problem situations in theoretical training for the purposes of forming thinking (Vieira & Tenreiro-Vieira, 2016). Therefore, the optimal learning tool is STEM-cases, each of the tasks of which is designed to form and diagnose one of the components of thinking (Solodikhina & Solodikhina, 2019). The cases are based on a real problem (or a chain of problem situations in a logical sequence).

For example, a problematic situation in one of the STEM-cases was the need to demonstrate to students the ecological situation around the damaged nuclear submarine. The natural science aspect of the problem is the effect of radiation on the underwater world, depending on the magnitude and duration of radiation. Students should analyze their scientific knowledge and supplement it to the level necessary for understanding and comprehending all aspects of the problem under consideration. The mathematical aspect is the construction of a mathematical model of this process, which allows you to study its essential aspects and discard the insignificant ones. At the same time, the complexity of modeling must correspond to the level of the most prepared students in order to implement the strategy of teaching some students to others during teamwork. The next block of tasks in the case "pushes" students to put forward an engineering idea for solving the problem and search for a technology that allows them to visualize the situation around the submarine. After solving this case, some of the students create 1–2 teams that develop educational laboratory work as a project. For example, one of the teams did a radiation laboratory in virtual reality. Students put on virtual reality goggles and feel like divers who can get close to the accident site and explore the territory both visually (environmental damage) and with a Geiger counter. The creation of this product developed programming skills, the ability to model 3D objects, knowledge of physics. The Technostartup course contains 3 similar STEM-cases related to the creation of virtual teaching equipment. But there are cases of other directions. For example, some problematic situations are devoted to the creation of underwater robots to collect garbage.

Studies have shown (Wahono et al., 2020) that the effectiveness of STEM implementation affects primarily the improvement of higher-order thinking skills, and only then affects academic knowledge and motivation, and the most effective way is to integrate STEM with project-based learning.

Since the components of business-thinking and design-thinking are the same, their development is carried out in the same way: first with the help of case studies, but with content based on archetypal situations of entrepreneurial activity, and then in working on a startup as a continuation of the project. For example, one of the entrepreneurial cases continues the idea of STEM-cases to create a set of educational virtual laboratory works in natural science (physics). Virtual laboratory work is necessary when studying processes that students cannot observe either because of the flow rates, or because of the scale of objects, or because of dangerous conditions. Among the tasks of the case are tasks for creating a financial plan, calculating economic indicators, analyzing the market and competitors, conducting in-depth interviews with potential buyers. As a result, it was revealed that this product (VR laboratory work in physics) is ready to be purchased by many educational institutions: state general education schools, technology parks and quantoriums, private centers for additional education. The project team won a grant of 500,000 rubles for the implementation of the technical part of the project and created 2 laboratory works in the virtual space. The implementation of such startups continues by students beyond the scope of the Technoinnovation course.

The problematic situation of the case is posed by the invited speakers based on personal experience, the theoretical material is given in the form of reference material necessary to solve a specific case, the discussion of the tasks of the case is carried out in the form of discussion, debate, business game, anti-conference. The final questions of the case have the form of an online quiz on the Kahoot platform using students' phones as remotes, preceding a self-reflection essay.

That is, training future innovators is based on two tools: working with two types of cases and creating a project that gradually as learning turns into a startup.

Competitiveness is an important aspect of project activity: at the end of the training, startups are evaluated by a competition committee consisting of entrepreneurs in the techniques and technologies field and potential employers. Studies had shown that "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" (Van Hanh, 2018).

5 Participants

Elements discussed above. The methodology was tested at the "Startup from Scratch" course (HSE) for two years. As a result, a new course "Technoinnovation" was created (HSE), where 123 students were trained in the format "STEM cases + project + entrepreneurial cases + startup" (experimental group), and 99 students - in the format "lectures + reports + startup" (control Group).

The adapted course was delivered to 58 high school students of the HSE Distributed Lyceum (high school students from more than 10 schools) in a mixed (full-time and distance) format, a similar course was delivered in a distance format for Russian schoolchildren (with international participation) at the Medeleev Center Technopark (76 people). Additionally, 36 HSE students were trained and became trackers (business mentors) of school teams in the adapted course.

6 Methodology of assessment thinking of innovator

Based on Figs. 3 and 4, the tools for the formation of thinking of innovator were assessed through functional literacy, components of thinking and motivation in the following areas:

1) descriptive self-assessment of the dynamics of the components of design- and business- thinking among students of the experimental group (the validity of STEM-case studies was studied and confirmed in (Solodikhina & Solodikhina, 2019));
2) comparative assessment of functional literacy among students of the experimental and control groups using tests and through the examination of startups;
3) comparative and descriptive assessment of motivation to follow-up activities to create technological innovations.

Work on cases and startups was carried out in groups of 3–4 people, which contributed to the development of both communication literacy and thinking through defending one's point of view in dialogue. The lecturer evaluated the solution of the case in points according to the parameters: novelty and productivity of the idea, correct planning and argumentation, risk assessment, quality of analytics. Process is important for the development of thinking. Therefore, students evaluated the process of work according to the criteria and distributed points among themselves so that the total score of the group for each parameter was equal to the lecturer's assessment. An exception is the lateral thinking assessment, where each idea and its weight were taken into account. The assessment was carried out on four parameters.

1. The number and productivity of the generated ideas, the willingness to pick up and develop someone else's thought. Evaluation mechanism: for example, for the novelty and productivity of the idea, the teacher gave 3 points, then the student who proposed two ideas, one of which the team members considered unpromising, and the second was used, receives $1 \cdot 1 + 3 \cdot 1 = 4$ points. If the lecturer gave the team 5 points (maximum), then the calculation for the same student becomes: $1 \cdot 1 + 5 \cdot 1 = 6$ points. If the productive idea has been significantly modernized by other members of the group, then the score given by the lecturer is divided among the co-authors of the idea. This score serves as an assessment of the student's lateral thinking.
2. Approach to the assessment of ideas (pragmatic or conditioned by emotions, personal attitude to the author of the idea), the quality of argumentation (how well the student's statements are justified, logical, understandable), the quality of planning (the detail of the Gantt chart and its correspondence to reality, the thoughtfulness of the material base and the choice of contractors). This score serves as an assessment of rational thinking.

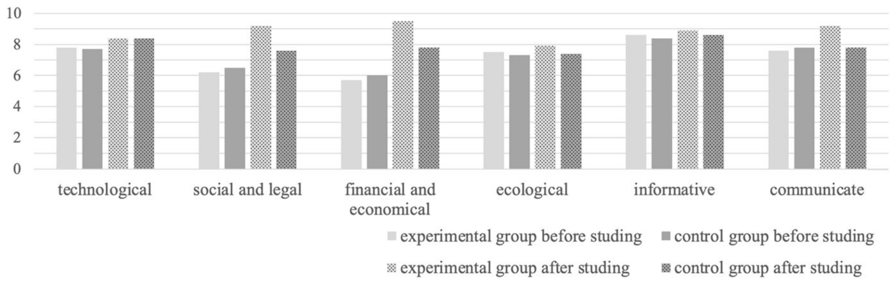

Fig. 5 Comparison of functional literacy before and after the course

3. The number of identified risks, difficulties and obstacles to the implementation of the idea, as well as contradictions, logical inconsistencies, errors in solving cases. The score serves as an assessment of the student's critical thinking.
4. The number of parameters by which the analysis is carried out at each stage of work, the quality of work with information (the ability to collect from different sources, determine reliability, consider from different points of view, systematize, establish multiple connections between elements). The score serves as an assessment of analytical thinking.

Since motivation influences the choice of activities related to or not related to technological innovation, the motivation for invention and entrepreneurship as the driving force of technological innovation was studied from the students of the experimental group. The instruments used in this study were observation sheets, questionnaires and interviews.

7 Discussing the results

A survey of 123 students in various fields of study at the HSE showed that the "STEM cases + project + entrepreneurial cases + startup" training format is attractive for 87% of students. Only 6% of students preferred the traditional format "lectures + reports + startup". 46% of students noted that this format contributes to a better perception of the course material and work on a startup.

Comparison of functional literacy (Fig. 5) confirmed this opinion. Functional literacy was assessed using specially designed tests. The assignments for high school students were based on the bank of assignments developed by the Institute for Education Development Strategy of the Russian Academy of Education"[5] and supplemented with similar tasks corresponding to the materials of the course "Technoinnovation" adapted for schoolchildren. The assessment of students' functional literacy was carried out using the tasks used at the HSE at the Department of Innovation

[5] The tasks are located in the public domain at the link: http://skiv.instrao.ru/bank-zadaniy/finansovaya-gramotnost/

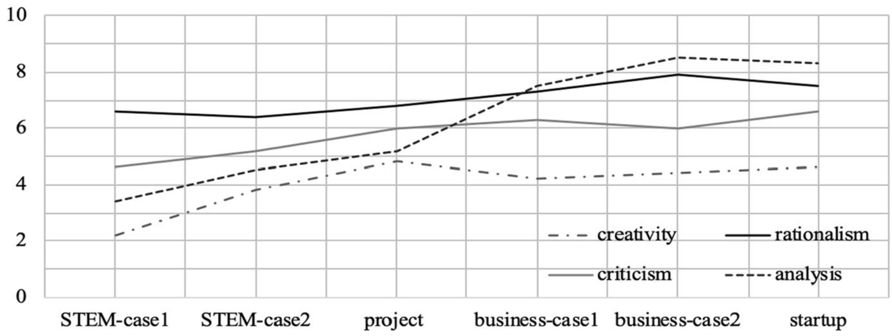

Fig. 6 Dynamics of changes in the components of innovator's thinking. The vertical scale is marked with points on a 10-point scale. On the horizontal - the average results of students for each of the thinking of innovator components, obtained when performing various tasks

Management during intermediate attestations. The following functional literacy was tested: technological, socio-legal, financial – economic, environmental, information and communication literacy. Testing of students of the control and experimental groups was carried out twice - before the start of the course "Technoinnovation" (ascertaining experiment) and after studying the course "Technoinnovation" (control experiment).

The comparison was carried out using the Student's t test. The ascertaining experiment showed that the initial literacy of the experimental and control groups coincided within the margin of error with a reliability of 0.95.

A control experiment showed that the training increased the literacy in both groups, but the level of socio-legal, financial, economic and communication literacy in the experimental group became statistically higher than in the control group. The results of technological, informational and environmental literacy in the control and experimental groups turned out to be the same within the margin of error with a reliability of 0.95.

The scores of the students of the experimental group, given by experts (entrepreneurs and business consultants) when defending startups, turned out to be statistically significantly higher than those of the students of the control group (8.9 and 9.7 points, respectively).

The assessment of the components of thinking was assessed according to the rules described above. Score control can be automated in the way suggested by Tan & Hsu (Tan & Hsu, 2018). Additionally, students completed two natural science cases, which can be used as a diagnostic tool for assessing different components of thinking (Solodikhina et al., 2020). The dynamics of the development of thinking components among students of the experimental group is given in Fig. 6, where all the received scores were converted to a 10-point scale. The growth of creativity took place at the stage of development of design-thinking due to the fact that students began to strive to offer as many ideas as possible, and at the stage of development of business-thinking, the growth of analytical thinking prevailed by increasing the parameters by which students carried out the analysis.

Motivation was assessed using the adapted Oparina test (Oparina, 2015). Descriptive assessment of students' motivation while working on a startup showed statistically significant shifts from the predominance of social motive to cognitive in 38% of students, from external to internal motivation in 16% of students, an increase in the desire to work in their specialty after graduation by an average of 1.4 points on an 8-point scale.

The results indicate that the proposed teaching methodology "two types of cases + a project moving into a startup" had a significant positive impact on all three parameters that are in the focus of the research: students' skills thinking of innovator, academic learning achievement and motivation. On the basis of the research, the course "Technological innovation" was developed for students of technical training.

Introduction to engineering education of the course "Technoinnovation" or similar, based on the same principles, will allow one to move one step towards the goal of modern education - the development of students' thinking. This course develops a special mindset in students - the mindset of an innovator. Such thinking will contribute to the fact that not individual engineers will strive to create new equipment and technologies, and then implement them, but many young engineers will be engaged in innovation. The desire and ability to create techno-innovations is important for the successful employment of young engineers themselves, and for the country as a whole, since an increase in the number of inventions will inevitably increase the innovativeness of the country's economy.

Authors' contribution Solodihina Anna: development and testing of the course, experiment conduct, data collection, data analysis, writing, peer review and discussion. Solodihina Maria: experiment preparation, methodological support of the course, data analysis, the concept, writing, expert analysis.

Data availability Research data are currently available only in Russian.

Code availability N/A

Declarations

Consent to participate The authors express their consent to participate.

Consent for publication The authors express their consent to the publication.

Conflict of interest The authors report no conflicts of interest.

References

Autor, D. (2019). Work of the past, work of the future. *AEA Papers And Proceedings, 109*, 1–32. https://doi.org/10.1257/pandp.20191110

Chernigovskaya, T. (2016). Languages of the person: brain and culture. *Psychophysiological and neurolinguistic aspects of the process of recognition of verbal and non-verbal patterns of communication*. St.-Petersburg: VVM. 11–16.

Crawley, E., Hosoi, A., & Mitra, A. (2018). Redesigning undergraduate engineering education at MIT - the new engineering education transformation (NEET) initiative. Paper presented at the *ASEE Annual Conference and Exposition, Conference Proceedings.*

Crawley, E., Bathe, M., Lavi, R., & Mitra, A. (2020). Implementing the NEET ways of thinking at MIT and assessing their efficacy. Paper presented at the *ASEE Annual Conference and Exposition,* .

De Bono, E. (1992). *Serious Creativity: Using The Power Of Lateral Thinking To Create New Ideas* (HarperBusiness) p. 145.

Devloo, T., Anseel, F., De Beuckelaer, A., & Feys, M. (2016). When the fire dies: Perceived success and support for innovation shape the motivating potential of innovative work behaviour. *European Journal of Work and Organizational Psychology, 25*(4), 512–524. https://doi.org/10.1080/1359432x.2016.1182157

Dynn, C., Agogino, A., Eris, O., Frey, D., & Leifer, L. (2006). Engineering design thinking, teaching, and learning. *IEEE Engineering Management Review, 34*(1), 65–65. https://doi.org/10.1109/emr.2006.1679078

Hayashida, H., & Katayama-Yoshida, H. (2012). Dynamic thinking process model of high-tech new material product development, *Proceedings of PICMET '12: Technology Management for Emerging Technologies*, Vancouver, BC, 2012, 2560–2569.

Kolko, J. (2018). The divisiveness of design thinking. *Interactions, 25*(3), 28–34. https://doi.org/10.1145/3194313

Koreshnikova Y. N. (2019) Critical thinking in modern society: what do universities provide? Monitoring of Public Opinion: Economic and Social Changes. No. 6. P. 91—110. https://doi.org/10.14515/monitoring.2019.6.06

Kumar, K., Zindani, D., & Davim, J. (2020). Design Thinking to Digital Thinking (SpringerBriefs in Applied Sciences and Technology), pp. 17–38.

Nemolochnov, E., & Solodikhina, M. (2016). Researching the needs of participants in project activities to create a specialized website. *Collection of scientific papers of the III All-Russian scientific-practical conference*, pp. 174–182.

Nygren, T., Haglund, J., Samuelsson, C., Af Geijerstam, Å., & Prytz, J. (2018). Critical thinking in national tests across four subjects in Swedish compulsory school. *Education Inquiry, 10*(1), 56–75. https://doi.org/10.1080/20004508.2018.147520

Oparina, A. (2015). The method of research of high school students" motivation to learning phisics. *Bulletin of the Tula State University. Series: Modern educational technologies in the teaching of natural science disciplines, 1*(14), 116–120

Plumanns, L., Janssen, D., Vossen, R., Hees, F., & Isenhardt, I. (2019). "How to Become an Entrepreneur?" Fostering Entrepreneurial Thinking of Engineers. *2019 IEEE Global Engineering Education Conference (EDUCON)*. https://doi.org/10.1109/educon.2019.8725031

Reed, J. (1998). Effect of a model for critical thinking on student achievement in primary source document analysis and interpretation, argumentative reasoning, critical thinking dispositions, and history content in a community college history course: *Ph.D. Dissertation, Graduate School University of South Florida Tampa, Florida*, 268 p. Available from: http://www.criticalthinking.org/resources/JReed-Dissertation.pdf. Accessed 21 Aug 2021

Rizvi, S., Donnelly, K., & Barber, M. (2012). Oceans of innovation. The Atlantic, the Pacific, Global Leadership and the Future of Education. *Education Issues*. No.4: 109–185.

Sharunova, A., Wang, Y., Kowalski, M., & Qureshi, A. (2020). Applying Bloom's taxonomy in transdisciplinary engineering design education. *International Journal Of Technology And Design Education.* https://doi.org/10.1007/s10798-020-09621-x

Shick, E., & Sharova, I. (2019) Analysis of innovation activity of Russia on the basis of international comparison. *Economic Research and Development*, *6*, 93–103

Solodikhina, M. (2019). The formation of thinking of future innovators in the educational activities of the project. *School and Production*, *3*, 15–22

Solodikhina, M., & Solodikhina, A. (2019). Development of critical thinking of master's degree students using STEM cases. *Education and Science, 21*(3), 125–153. https://doi.org/10.17853/1994-5639-2019-3-125-153

Solodikhina, M., Odintsova, N., & Odintsova, E. (2020). Natural-scientific cases as an instrument for assessment of logical thinking. *Journal of Physics: Conference Series, 1691*, 012218. https://doi.org/10.1088/1742-6596/1691/1/012218

Szenes, E., Tilakaratna, N., & Maton, K. (2015). The knowledge practices of critical thinking. In M. Davies & R. Barnett (Eds.), *The Palgrave handbook of critical thinking in higher education* (pp. 573–591). Palgave Macmillan. https://doi.org/10.1057/9781137378057_34
Tan, P., & Hsu, M. (2018). Designing a System for English Evaluation and Teaching Devices: A PZB and TAM Model Analysis. *EURASIA Journal Of Mathematics, Science And Technology Education, 14*(6). https://doi.org/10.29333/ejmste/86467
Van Hanh, N. (2018). The real value of experiential learning project through contest in engineering design course: A descriptive study of students' perspective. *International Journal of Mechanical Engineering Education, 48*(3), 221–240. https://doi.org/10.1177/0306419018812659
Vieira, R., & Tenreiro-Vieira, C. (2016). Teaching strategies and critical thinking abilities in science teacher education. *Critical thinking: Theories, methods and challenges*. 77–98.
Wahono, B., Lin, P., & Chang, C. (2020). Evidence of STEM enactment effectiveness in Asian student learning outcomes. *International Journal Of STEM Education, 7*(1). https://doi.org/10.1186/s40594-020-00236-1
Yıldırım, B., & Sevi, M. (2016). Examination of the effects of STEM education integrated as a part of science, technology, society and environment courses. *Journal Of Human Sciences, 13*(3), 3684–3695. https://doi.org/10.14687/jhs.v13i3.3876
Zhu, Q. (2020). Exploring how to build innovation and entrepreneurship education ecosystems in universities in Guangdong against the backdrop of the Guangdong-Hong Kong-Macau Greater Bay Area. *E3S Web Of Conferences*, *165*, 02005. https://doi.org/10.1051/e3sconf/202016502005

Authors and Affiliations

Anna Solodikhina[1] · Maria Solodikhina[2,3]

Maria Solodikhina
mv.solodikhina@mpgu.su; solodikhina-mv@rudn.ru

1 National Research University Higher School of Economics (HSE University), 11 Pokrovsky Bulvar, Moscow, Russian Federation

2 MPGU International Relations Office Moscow Pedagogical State University (MPGU), 1/1 Malaya Pirogovskaya Str, Moscow, Russian Federation

3 Peoples' Friendship University of Russia (RUDN), Miklukho-Maklaya str.6, Moscow, Russian Federation