Modernization of math-related courses in engineering education in Russia based on best practices in European and Russian universities

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INTRODUCTION

Engineering education in general and in the field of information technology in particular, tends to be more and more attractive to Russian students in response to the growing demands of the labour market in this area.

However, nowadays there are several serious problems in this area.

These problems, firstly, include global changes in the world which certainly affect education. The speed with which engineering knowledge and competencies are updated has been steadily increasing, new skills required by engineers constantly emerge while some of the existing ones become obsolete. Sometimes it even happens that some technology or professional standard becomes outdated before the student completes a four-year bachelor course of study at a university. Engineering problems evolve due to the penetration of technology into all areas of our lives.

This, in turn, complicates the process of learning. Modern student is obliged not only to master a certain amount of knowledge but also learn how to use it to solve practical problems, and secondly, and most importantly, learn how to solve not typical problems, which are not dealt with explicitly during training and lie on the intersection of different fields. This requires formation of respective competencies within the student but it also gives rise to the following problem. There is a contradiction between necessity to increase independence and initiativity of a student in the learning process and the existing unpreparedness of the majority of students to such a form of education. Another contradiction is the contradiction of the goal to form the competencies associated with general intellectual and creative development of students and the necessity to ensure at the same time the theoretical preparedness of a student for professional work and his or her possession of specific knowledge and a number of skills.

Secondly, there is a very serious problem of the high percentage of drop-outs during the first year of study in STEM courses. Mathematical disciplines are the most typical reason for that. According to the current statistics, the average drop-out rate from engineering specialties because of mathematics in Russian universities is about 20%, for some curricula it reaches 40%.

School graduates, who choose these courses, usually underestimate the role and place of mathematics in their upcoming education. Often, prospective students have this false perception that mathematics is unimportant for a chemist, a physicist or a programmer. As a result, not all such students are able to continue their education when they are faced with such disciplines like calculus, probability theory and mathematical statistics, theory of differential equations and others during their first year of study. Everything is also aggravated by the difference in the level of mathematical training between universities and schools.

After the introduction of CSE (EGE), most Russian universities started to conduct their own entrance tests for independent assessment the level of education of enrolled students. An example of input test in elementary mathematics and its results carried out among first-year students in one of the Russian universities in 2015 are presented below.

Input test consisted of ten tasks, for each of which one score was assigned:

- rational inequalities, method of intervals – 1 task,
- absolute values – 1 task,
- irrational equations and inequalities – 1 task,
- exponential and logarithmic equations and inequalities – 1 task,
- function plots – 3 tasks,
- set of points on plane, satisfying a relation – 3 tasks.

It is worth emphasizing that all these topics are included in the basic school curriculum of elementary mathematics and do not contain tasks of high difficulty level. The histogram below shows the distribution of the results: the y-axis shows the percentage of students who performed the test with the corresponding sum of points, and the x-axis represents sums of scores.

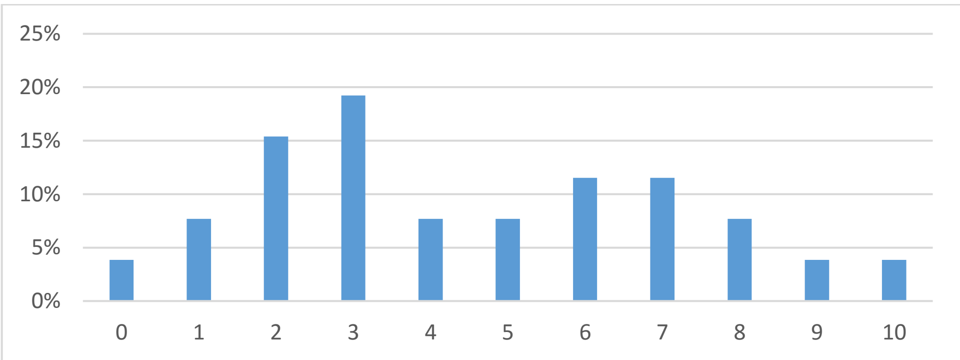

Fig. 1. Distribution of the results of input test in elementary mathematics

If we assume 50% to be a threshold of successful completion of the test (it is customary for evaluation system in Russian universities), then one can see from the graph that more than half of first-year students failed the test, and the level of knowledge of the rest of the students is average.

At the same time numerous studies have shown that the level of mathematical knowledge is a major factor determining the success of engineering education. Mathematics is the fundamental discipline for the entire spectrum of STEM curricula.

In Russia all university students pursuing this kind of curricula are obliged to take a lot of math-related courses at the beginning of their education. Disciplines of engineering profile for which the mathematical knowledge and skills are essential input requirement appear only during senior years.

Other reasons for the above-mentioned problems in Russian universities include reduction of teaching hours (credits) for math subjects in curricula of some Russian universities and the fact that new information technologies are not used to the full extent in education process. The European experiences and research results have proven that significant improvements in learning outcomes in mathematics can be achieved by applying new Technology-Enhanced Learning (TEL) tools and pedagogic approaches. It has been proven that due to the application-oriented nature of math studies within STEM curricula the uptake of modern TEL methods has a maximum effect on overall quality of education.

Due to the aforementioned problems, employers' access to human resources is limited and they are forced to seek possible solutions to the problem together with universities, because in spite of a more or less sufficient number of graduates of specialized areas of engineering training, their professional level does not fully meet the needs of the business community.

Because of these circumstances, much methodological work is required to upgrade the system of mathematical education for engineers in Russian universities.

This problem was addressed by international TEMPUS project MetaMath which involves five Russian universities (Tver State University, Lobachevsky State University of Nizhniy Novgorod, Kazan National Research Technical University named after A.N.Tupolev, Ogarev Mordovia State University, Saint-Petersburg Electrotechnical University (LETI)), Association for Engineering Education of Russia and four European universities (Tampere University of Technology, Claude Bernard University Lyon 1, Saarland University, Chemnitz University of Technology). This project's aim is the modernization of the Russian education system in accordance with international trends, best practices of European universities and account of Russia's cultural and educational traditions as well as needs of business and industry.

The following material was put at the basis of modernization methodology:

- competence-based approach of the SEFI framework,
- analysis of the Russian federal standards of higher education,
- the results of one of the previous TEMPUS project TUNING Russia,
- series of studies in Russian universities, including sociological surveys of students' motivation for choosing engineering education, surveys of employers, graduates, university community, students about their satisfaction with the quality of learning outcomes.

The purpose of this article is to describe research results and analyse the experience of modernization of educational programs based on the produced methodology.

1 THE STRUCTURE OF MATHEMATICAL COMPONENT IN ENGINEERING PROGRAMS IN RUSSIAN UNIVERSITIES

As mentioned above, all students of engineering programs in Russian universities have a significant number of mathematical disciplines in the early years of their education. We briefly describe the structure of the mathematical component in bachelor engineering programs.

Bachelor programs consists of 240 credits. Duration of study is 4 years with one academic year having 60 credits.

The following table represents a list of core mathematical courses which is more or less alike in all educational programs of engineering profile in Russian universities.

Table 1. List of core mathematical courses

Course	Semester / Year of Study	Credits	Hours
Calculus 1 (theory of limits, the classes of functions, continuity and differentiability, the fundamental theorems of differential calculus, the use of derivative)	1 / 1	5	Lectures – 54 Workshops – 54
Calculus 2 (function of several variables, geometric applications of the derivative, the complex functions of a real argument, the indefinite integral, methods of integration, definite integral, numerical and functional series and signs of convergence, expansion of the function in a Taylor series)	2 / 1	5	Lectures – 57 Workshops –57
Calculus 3 (improper integrals, multiple integrals, surface integrals and their applications, integrals depending on a parameter)	3 / 2	6	Lectures – 54 Workshops -54
Linear Algebra and Geometry (vector spaces and matrix algebra, matrices and determinants, systems of linear equations)	1, 2 / 1	10	Lectures – 108 Workshops -108
Probability Theory and Mathematical Statistics (probability space axioms, random variables and their distributions, statistical hypothesis)	4,5 / 2,3	10	Lectures – 74 Workshops -74
Discrete Mathematics (elements of combinatorics, Boolean functions, graphs, use graphs to represent Boolean functions, finite automata, algorithms, recursive functions)	1, 2 / 1	8	Lectures – 72 Workshops -72
Differential Equations (first order differential equations, integral curves, Cauchy problem, the method of successive approximations, equation of order n, finding the fundamental system of solutions of systems of ordinary differential equations, problems of the qualitative theory of differential equations, difference equations and their solutions,)	4 / 2	3	Lectures – 38 Workshops - 38

Optimization Methods (mathematical model of operations, strategy, and their types, multicriteria problems of choice and decision-making necessary conditions for a maximin, decision-making in conflict situations, noncooperative games and hierarchical, network problem, minimization of functions of one variable, methods for finding absolute extrema of functions of several variables, conditional search methods extrema of functions of several variables, the optimal control problem)	4 / 2	6	Lectures – 70 Workshops – 35
Numerical Methods (theory of errors, interpolation and approximation of functions, numerical differentiation and integration, direct methods for solving systems of linear algebraic equations, iterative methods for solving systems of linear equations, methods for finding solutions of nonlinear equations and systems, methods for solving eigenvalue problem, numerical methods for solving the Cauchy problem and boundary value problems for ordinary differential equations and systems)	3 / 2	5	Lectures – 70 Workshops – 35

As the table shows, basic mathematical training is carried out during first two years of study, while all special disciplines appear during third and fourth years.

2 THE ATTITUDE OF STUDENTS TOWARDS MATHEMATICS

As part of the research a series of sociological surveys among the students was conducted to determine their attitude towards mathematics.

2.1 «Mathematics through the eyes of students»

The first survey – "Mathematics through the eyes of students" was devoted to students' attitudes toward mathematics “per se” and role which they assign to it among other sciences.

This survey was carried out as part of a broader sociological research, conducted by the University Claude Bernard Lyon 1, with the participation of universities from Russia, France, Germany, Finland, Georgia and Armenia. Preliminary analysis shows the difference between the accents in the results depending on the country. If we take only Russian universities one can also see the differences, but not that significant. Since the research is still in progress and is conducted by another university, we cannot publish it, but as an example we present its results for one of Russian universities, namely Tver State University, which was conducted among 200 full-time students from 1 to 4 years of study (bachelor programs) and 1 and 2 years of study (master programs).

There are seven responses for each question:

- don't know
- 0 - completely disagree
- 1 - disagree
- 2 - rather disagree
- 3 - rather agree
- 4 - agree
- 5 - completely agree

The results are shown as a percentage of the total number of survey participants.

Table 2. Results of survey "Mathematics through the eyes of students"

№	Question	Don't know	0	1	2	3	4	5
1	Mathematics have an interest, especially for solving concrete problems	1	2	2	8	21	35	31
2	Mathematics are used primarily to model phenomena	6	3	3	13	37	23	14
3	Mathematics explain facts in reality	4	6	8	12	28	24	19
4	Mathematics are used mostly in technical domains	2	11	6	9	24	24	24
5	Mathematics are useless in everyday life	1	57	10	14	11	5	2
6	Only applied mathematics are interesting	6	20	9	25	16	12	11
7	Mathematics are useful in all sciences	2	2	2	6	15	31	43
8	Mathematics serve no purpose in human sciences	5	28	20	14	13	9	11
9	Human relationships cannot be explained by mathematics	12	11	9	10	15	18	25
10	Natural phenomena are too complex to be apprehended by mathematics	9	21	13	19	22	9	7
11	Mathematics can be applied to man crafted objects and much less to objects found in nature	8	20	13	12	22	17	9
12	Learning mathematics in early classes serves mostly the purpose to help the children get around in life	9	9	7	9	24	23	19
13	In engineer school, mathematics are mostly pure and abstract	42	9	8	10	21	7	4
14	We need more applied mathematics in engineer training	25	2	1	6	24	21	21
15	In engineer school, theory is taught without taking into account its applications	36	12	8	10	19	9	6
16	Math teachers think they possess truth	27	8	7	10	21	14	12
17	There is almost no connection between math teaching and the engineer job reality	15	21	13	16	17	13	6
18	Math teaching doesn't try to establish links with other sciences	4	43	18	14	10	6	3
19	Mathematics weight too much in engineer training	24	16	7	18	20	5	10

20	Mathematics cannot be avoided in engineer training	12	1	2	2	10	17	57
21	A teacher only purpose is to bring knowledge to students	2	16	6	12	28	21	14
22	The structure of math courses doesn't allow learning autonomy	5	28	9	20	18	13	6
23	With new means available to students, learning is no longer required, one just has to quickly find solutions to problems that are encountered	2	40	17	15	15	8	3
24	Math teaching evolves according to changes in society, for example integrating new technology	5	5	7	12	24	28	19
25	"Courses haven't changed in the last decades when the world is evolving greatly and fast"	12	16	11	13	20	17	12
26	Math teaching for engineers is a one way process: knowledge flows from the teacher to the students	18	10	7	14	18	17	15
27	In mathematics, there is nothing left to discover	9	55	13	12	6	3	1
28	Mathematics are only a tool for science	9	31	10	11	19	13	7
29	Mathematics objects are not real	7	38	13	13	16	7	7
30	Three is no room for creativity and imagination in mathematics	4	50	16	7	8	6	8
31	Mathematics raised from concrete needs	12	11	6	10	26	25	10
32	There is no room for uncertainty in mathematics	5	27	10	9	23	11	15
33	Only math can approach truth	9	21	6	14	25	16	9
34	Mathematics are only an abstraction, they don't deal with reality	5	48	13	12	15	6	1
35	Mathematics necessarily mitigate what they model	14	11	10	16	27	14	9
36	Mathematics really explain only what is man made	8	25	12	17	18	13	8
37	A mathematical model is necessarily limited	14	23	14	9	19	15	6
38	A mathematical theory can not be refuted	9	32	16	14	10	13	6
39	Mathematics have no meaning in real life, they don't represent anything real	3	56	16	11	11	2	1
40	Mathematics can not be the subject of a conversation (contrarily to literature or philosophy)	2	50	14	13	10	5	6
41	Mathematics are better left to experts and initiated people	3	34	9	9	21	15	9
42	Mathematics are a human construction	10	6	2	6	17	19	39
43	Mathematics are universal	5	2	3	5	20	27	37
44	Mathematics only approximate and mitigate what they study	7	44	14	17	13	3	2
45	To be good at math means to be good at everything	5	25	9	12	20	14	14

46	Usual words have the same meaning in real life and in math sentences	13	24	16	18	16	8	4
47	In mathematics, it's possible to find new theories	5	0	1	6	16	24	49

Analysis of the results shows that students have an understanding that mathematics is a key discipline in the engineering training, and there is a "belief" that mathematics can help to adequately explore the world around us - at least with the help of natural sciences.

It is also interesting to look at attitude of students of different courses to the same question. Fig. 4 and 5 in particular show how the attitude towards mathematics as a tool for the humanities changes.

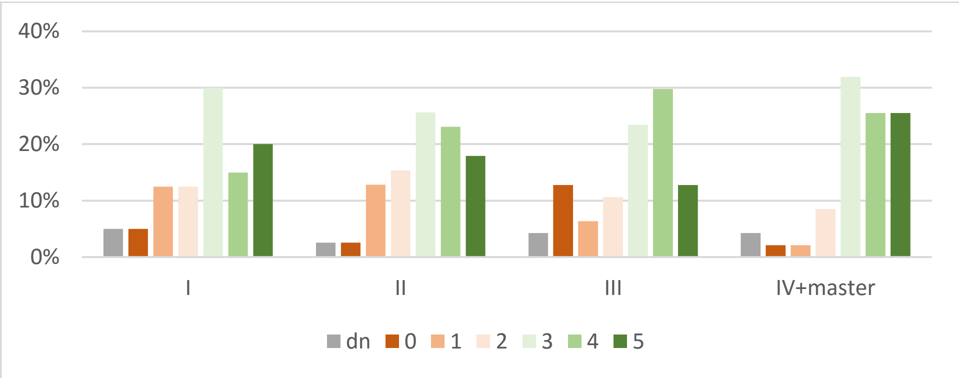

Fig. 2. Mathematics explain facts in reality

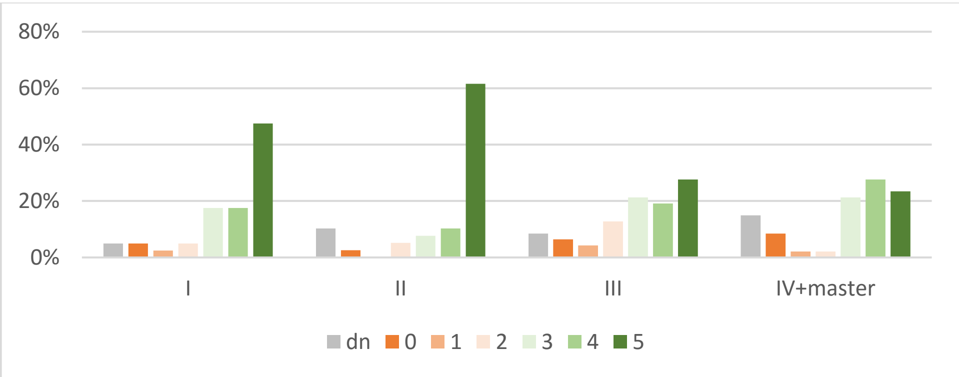

Fig. 3. Mathematics are a human construction

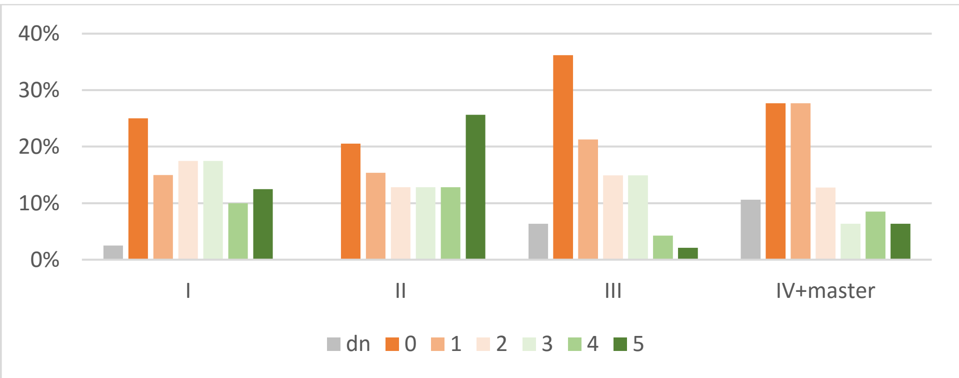

Fig. 4. Mathematics serve no purpose in human sciences

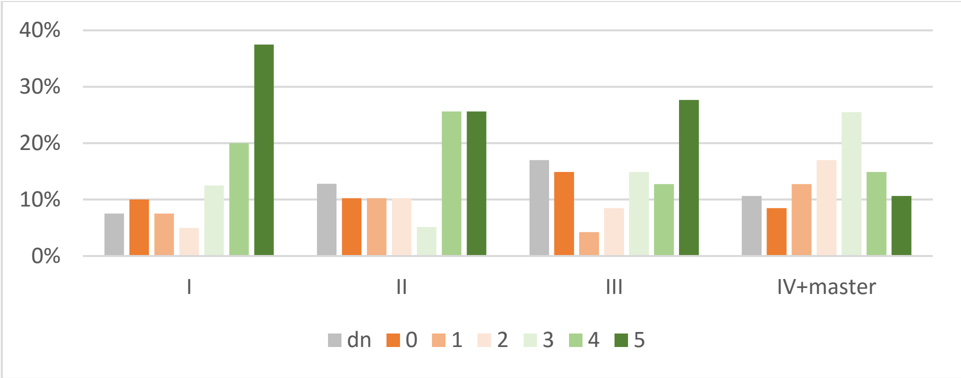

Fig. 5. Human relationships can not be explained by mathematics

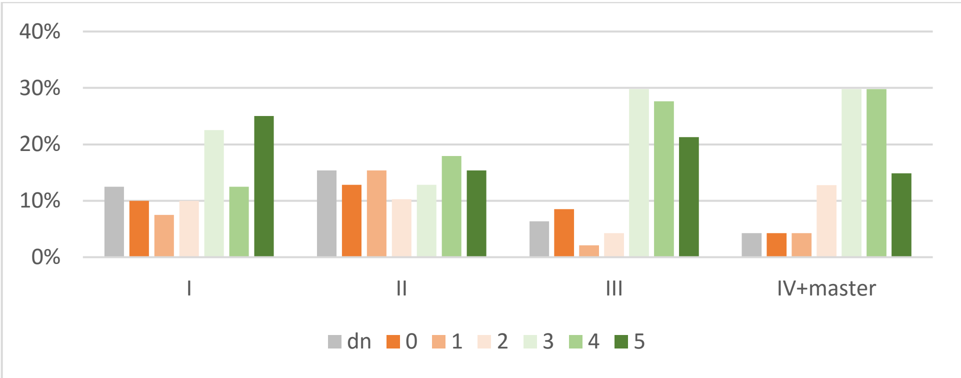

Fig. 6. Learning mathematics in early classes serves mostly the purpose to help the children get around in life

The graph in Fig. 6 is curious. It can be interpreted as follows. First-year students who are actually "yesterday" school pupils responded to the question having strong memories of school education. Second-year students are in the "epicenter" of mathematics education, thus the distribution is almost uniform which indicates that the students have little time and desire to think about mathematics in general because there is too much of it in their lives already. However, by the end of training, they begin to realize the importance of the role and place of mathematics education in their future life.

2.2 «Mathematics in the life of students»

The second survey was devoted to the study of students' attitudes towards mathematics as a discipline of their study and its role in their future profession. The survey has the same scale of responses, like the first one, except for the answer "I do not know." Values are expressed as a percentage of the total number of participants. The survey was conducted among students of 3d and 4th years of study. Number of surveyed students is around 100.

Table 3. Results of survey "Mathematics in the life of students"

№	Question	0	1	2	3	4	5
1	I think solving math problems is quite boring	5	33	40	12	7	3
2	Solving math problems is fun	4	1	13	48	29	4

3	The entire process of solving mathematical problems is very engaging for me	3	5	17	49	16	9
4	I am OK with how I am doing at solving math problems	0	11	20	51	15	4
5	I consider solving math problems as an opportunity to prove myself	7	21	29	29	11	3
6	I think mathematics is very interesting	0	5	17	36	29	12
7	I liked working on math problems	0	4	24	49	17	5
8	I find mathematics to be very hard	8	21	39	25	5	1
9	I think I am very good in math	1	3	21	49	23	3
10	I think I have a talent for mathematics	7	17	32	32	8	4
11	It is very important for me to be able solve math problems	3	7	12	40	31	8
12	I think math problems are very boring	1	15	19	28	23	15
13	I worry a lot about the tasks, which I am not sure I can master	3	8	19	35	29	7
14	I like situations, in which I have to prove my skills	0	8	5	32	37	17
15	I am afraid to make mistakes even if they might pass unnoticed	3	17	17	24	28	11
16	I try to do my best when solving math problems	1	4	17	56	19	3
17	I like tasks that show what I am good at	0	1	1	36	37	24
18	I prefer easy tasks, in which I know I won't make any mistake	0	4	4	41	33	17
19	I am scared to have to solve exercises that might cause me making mistakes	0	13	29	28	25	4
20	I think, in math, main principles are more important than applied knowledge	1	12	41	27	16	1
21	I enjoy theoretical aspects of mathematics more than practical problem solving	8	33	36	19	4	0
22	I think for an engineer, problem solving skills are more important than math theory	0	11	19	36	28	7
23	I think we need fewer mathematics course in university	5	7	47	28	11	3
24	I think for my future studies at this university, mathematics has little importance	8	28	35	15	7	8
25	I think for my future career, mathematics has little importance	8	17	29	20	16	9
26	I think, all technical subjects require math knowledge	0	0	7	32	51	11
27	I think, I need to study math to be successful in the future	3	5	24	40	21	7

The poll has a series of similar questions asked in different terms, which allows to check the results on "random selection". It is clear from the data that students responded consciously and by analyzing their answers one can come to the following conclusions.

Firstly, students prefer more practical mathematics, rather than theoretical. At the same time, they consider reduction of credits for mathematical disciplines inappropriate, because they believe mathematics to be important for studying other disciplines. Second, students consider mathematics to a lesser extent essential for their future lives and careers. Thirdly, the students believe that for an engineer practical problem solving skills are more important than theoretical understanding of the principles, on which these methods are based.

Polls generally show that students are aware of the importance of mathematics at least for their further education at university.

3 RESULTS OF COMPARATIVE ANALYSIS AND APPROACHES FOR MODERNIZATION

In order to achieve the goal of upgrading system of mathematical education, the structure and content of educational process in math-related engineering courses in the selected Russian and European universities have been studied, comparative analysis was held and, as a result, recommendations for the best practices implementation in the educational process of Russian universities were elaborated.

Comparative analysis shown that thematic contents and learning outcomes in Russian and European universities are almost identical. The main difference is observed in active use of information technologies and, in particular, e-learning systems in European universities. This allows to take out some of the material for independent study and focus on really difficult topics. E-learning systems also allow to automate and, as a result, simplify the knowledge assessment process.

As a result of comparative analysis, the following ways for modernization of courses were developed:

- There are two ways of teaching math: theory-oriented and practice-oriented. We should find a golden mean but make emphasis on practice.
- Give more real-life practical examples in math subjects from the very beginning to justify necessity of math.
- Involve business community to participate in students practice: starting from term papers and finishing with a diploma and industrial practice.
- Increase the role of independent work of students.
- Use the project method of teaching. The main purpose of this method is to provide students with possibility of independent knowledge acquiring while solving practical problems that require integration of skills from different subject areas. Tasks which have to be solved are applied and this, in turn, demonstrates the importance of mathematics in solving real life problems and thus improve students' motivation to study it.
- Use bridging courses to simplify students' transition from school to university.
- Use ICT tools and technologies more actively to enhance and support education process.

4 PRELIMINARY RESULTS OF AN EXPERIMENT

In the course of the project an experiment was conducted and approbation of the developed modernization methodology in the Russian universities was carried out. As part of the experiment, several groups of students in each institution took the modernized courses. Various test methodologies that assess motivation and dynamics of students' knowledge gain were used in order to evaluate the effectiveness and adequacy of selected approaches. Not only the selected disciplines have been modernized but also some changes to curricula were made. Participants of the project changed the structure of credits distribution and the sequence in which some of the subjects are studied. This work is conducted in accordance with the general process of refining of federal state standards of higher education in Russia which takes into account the requirements of employers, due to the participation of authors of the article in the relevant working groups of the Ministry of Education.

We describe the results of an experiment in one of the Russian universities. One group of students of third year studied mathematical modelling course ("Mathematical models of natural science") during the fall semester of the 2015-16 academic year basing on the traditional program, another group of students – basing on modernized program. Testing in the framework of SEFI competencies was used in order to test and compare the results of program mastering. Working group analysed not only the competences at the formation of which this discipline was directly aimed but more importantly competences of mastering of basic mathematical knowledge used in the discipline (mathematical analysis, differential equations, optimization theory).

At the beginning of the course testing of input level of students was carried out and at the end - the final test. Input and output tests were carried out in the same framework of competencies on the same level of complexity which helped to reveal the knowledge gain of students. Test results are shown in the following tables. The first table shows level of mastering aggregated groups of SEFI competences, the second provides the results for individual SEFI competencies. The test results are indicated as a percentage of correctly accomplished tasks.

Table 4. The relative level of mastering aggregated groups of SEFI competences at the beginning and end of the course

№	SEFI competences (aggregated group)	1st group (traditional program)		2nd group (modernized program)	
		Pre-test (%)	Post-test (%)	Pre-test (%)	Post-test (%)
1	ordinary differential equations	33,60	40,69	43,33	63,75
2	equations of the first order	63,00	52,59	62,50	73,44
3	second-order equations	57,14	54,19	40,48	67,86
4	tasks associated with eigenvalues	91,20	78,62	63,33	72,50
5	nonlinear optimization	92,00	75,86	83,33	100,00

Table 5. The relative level of mastering individual SEFI competences at the beginning and end of the course

№	Individual SEFI competences	1st group (traditional program)		2nd group (modernized program)	
		Pre-test (%)	Post-test (%)	Pre-test (%)	Post-test (%)
2.1	Determination of the equation with separable variables	64,37	60,92	72,22	95,83
2.2	Finding the general solution of differential equation	55,17	58,05	69,44	77,08
2.3	Exact differential equations and its solution	65,52	24,14	16,67	37,50

3.1	Construction of a particular solution for the simplest right parts; Construction of the general solution of the equation; use the initial conditions to calculate a particular solution	27,59	20,69	33,33	75,00
3.2	The concept of resonance	41,38	62,07	33,33	56,25
3.3	Second-order equations with constant coefficients and its relationship with the oscillation simulation	58,62	37,93	41,67	75,00
3.4	Fundamental solutions and their interpretation in terms of the model	58,62	79,31	50,00	68,75

Table 6. Relative increase / decline in the level of mastering SEFI competencies (knowledge gain)

№	SEFI competences (aggregated group)	1st group (traditional program)	2nd group (modernized program)
1	ordinary differential equations	21,10	47,13
2	equations of the first order	-16,52	17,50
3	second-order equations	-5,16	67,64
4	tasks associated with eigenvalues	-13,79	14,48
5	nonlinear optimization	-17,54	20,00

The results of the test show that for a number of competences, for example, "ordinary differential equations" and "second-order equations", modernized program provides a higher degree of mastering by students in absolute terms. It is even more noticeable that the modernized program gives best results in knowledge gain (difference between the results of pre- and post-test, Table 3). But the most interesting thing is that traditional program gives negative knowledge gain for number of competencies (for example, "first-order equations", where the decline is 16.5% and "non-linear optimization" with decline 17.5%), while the modernized program shows no decline anywhere.

This can be explained by the fact that during the process of traditional education not much attention is given to these competences. It is believed that they were mastered during previous courses and there is no need or time to repeat it. As a result, students forget even what they knew before. On the contrary, the modernized program allows students to update their basic knowledge with the help of independent work and applied nature of the tasks, even if it is not directly connected with the material of lectures.

5 SUMMARY AND ACKNOWLEDGMENTS

The article describes problems in the area of engineering education in Russia. These problems were addressed by international TEMPUS project which involves several Russian universities, Association for Engineering Education of Russia and four European universities (Tampere University of Technology, Claude Bernard University Lyon 1, Saarland University, Chemnitz University of Technology). This project's aim is the modernization of the Russian education system in accordance with international trends, best practices of European universities and account of Russia's cultural and educational traditions as well as needs of business and industry.

The article analyses the experience of modernization of educational programs based on produced methodology. Currently obtained results of approbation of the methodology showed that the chosen modernization methods are an effective tool for solving the designated math-related problems in engineering education in Russian universities and, consequently, students will start to correspond more adequately to the labour market needs.

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