Systems engineering – an important component of modern engineering education

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The article discusses the necessity to introduce systems engineering into engineering education programs. It characterizes the systems engineering methodology, states the necessity of systems engineering education. The paper deals with the problems of systems engineering education management and the requirements to the education programs in this field. It proves that systems engineering training is one of the key ways to the formation of new generation of engineers who can create competitive systems for the world market.

Key words: *systems engineering, engineering education, competitive system, educational programs.*

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Introduction

Russian high-tech enterprises feel shortage of engineers who can make competitive products and services. As a result, big companies of nuclear, energy, space, military (defense) and other branches have to influence on the educational market asking for implementation of the world level education programs on the one hand. On the other hand, they have to invite more and more foreign specialists, that takes a lot of resources.

The crisis phenomena are increasing at a time when most of Russian technical universities are not ready for production of graduates who are capable of free and creative engineering work in the market economy. These conditions make the engineers use not only the basic fundamental knowledge but also put and solve the tasks of science and technical development [1].

On the other hand, the problems in the sphere of engineering training are being exacerbated because of objective changes going on in the environment, such as:

- unprecedented complicacy of the basic engineering product – systems;
- fast emergence and development of new technologies with simultaneous necessity to prolong (sometimes more than once) a life cycle of the systems having been put into operation;
- constantly increasing competition on the market of engineering products and services;
- rapid complicacy of engineering activity both its management and implementation components.

The abilities needed for creators of complex modern systems are formed and developed at the student stage. That is why it is possible to reach the main goal – the formation of an engineer capable of making systems competitive in the world market - at the stage of basic university training. In these conditions Russian technical universi-

ties are required high professional level, constant education programs improvement, and creative use of foreign colleges' achievement taking into account Russian realities on the educational service market.

The analytical report [2], made by a group of famous Russian specialists, states that the ideology basis of Russian vocational education is the idea of what the specialist should be, what the training technique is and how to make a specialist of a certain quality. But there is no idea about the specialty. The analysis shows that while the number of specialties is growing and the requirements to the specialists are increasing the career success doesn't depend on the specialty written in a diploma. The authors of the above mentioned report make a reasonable conclusion that Russian Higher Education's Doctrine is doubtful so far as relevant to the content and management of educational process and student training as the higher educational establishment can give knowledge and competencies to the graduate, but the graduate can become a real specialist only after acquiring some practical professional experience.

In spite of more than 20 years of stagnation in the sphere of complex systems and new technology development, our specialists are still able to develop high-tech systems and to support their full life cycle (LC). But on the whole, the competitiveness of the systems made by Russian specialists in recent years is constantly decreasing. In authors' opinion, such situation is basically the result of the following: Russian enterprises and Higher Engineering School underestimate the key role of systems engineering in ensuring competitiveness of Russian engineering systems. It is systems engineering and it's most important components such as program engineering, requirement engineering, changes management, architectural design that make the basis for a sustainable construction to support the connection between mission, strategic goals, aims and measurable results of engineering activity.

In light of this, a special role of education in the sphere of systems engineering becomes obvious. It is important for training engineers in different fields: mechanics, radio engineers, nuclear engineers, aviation engineers, bioengineers, program engineers and other specialists working on systems and their elements. The thing is that the basic task for systems engineering is to give a method and an instrument to the interested parts to create effective systems of different classes that meet the people's needs. To solve this task, the systems engineering, being developed as a complex approach, is focused on the core of engineering activity. It studies its key aspects in their interaction. Thus, the systems engineering, if included into education programs of engineering training, can become the basis to form a new body of engineering training programs for different spheres. It can be the foundation that makes possible to create a complex of competences necessary for graduates to be successfully adjusted to various professional engineering practices.

Systems engineering methodology

Systems engineering as a new applied system methodology appeared in the middle of the 20th century as a response to sharp complicacy of scientific, technical and management problems, on the one hand, and to the growth of responsibility for the results of these activities, on the other hand [3, 4]. Nowadays the international scientific and industrial communities recognize the systems engineering as a methodological basis to create systems of any classes and purposes. There are several directions where the systems engineering puts most efforts. They are the performance management to develop systems; staff training; standardization, development and support of systems engineering and some other [5].

In foreign scientific and methodical works the systems engineering is formulated as interdisciplinary approach and methods determining a full set of technical and management efforts to transform needs of a customer and other interested parts, expectations and limits into a system solution and to support it during its life time [6].

It was A. Hall who first described the systems engineering methodology more than 40 years ago [4]. He determined it as an organized creative technology and characterized the following statements as the basic ones.

Firstly – the systems engineering is multidimensional and this fact is to be surely reflected while determining its subject.

Secondly – the systems engineer should be aware that the goal of the whole systems engineering process is to make optimal boundaries between human's inter-

ests, the system and its environment. The environment consists of three components:

- physical and technical environment
- business and marketing environment
- social environment.

Thirdly – the systems engineering studies first of all needs. This study should be based on the advanced economic theories, market demands and the possibility to change these demands now and in the future as well.

Another important feature of the systems engineering is its close interaction with systems thinking. Actually, the main idea of systems thinking is to detect, observe and realize complex emergent behavior resulting from dynamic systems interaction in working process. But the ability to act using systems' language, which is so important for an engineer, is not described in the works devoted to the systems thinking. It is exactly this point, as H. Lowson underlines [7], where the systems engineering adds to the systems thinking. This feature of the systems engineering proves the importance to study it for a modern engineer's world outlook.

Thus, from the very beginning of the systems engineering development and up to now the basis of engineering activity is considered to be system complex and joint use of technical, economic, management and other disciplines' achievements. It is this approach that gives special relevance to the systems engineering and makes it possible to use its achievements to build developing systems of different nature and purpose. This approach distinguish (but not oppose) the systems engineering from other more familiar for Russian specialists subjects such as quality management, project management, supply chain management, resource management, risk management and other.

The core of the subject "systems engineering" is underlined by many specialists: the systems engineering is focused to solve both management and design problems within the framework of full LC management. A.P. Sage, a leading authority, points out that the systems engineering is the management technology focused on control of full LC processes to choose, develop and apply the most effective, reliable and quality systems to meet customers' demands [8].

LC is understood as the development process of a system, product, service or other human made object form its idea and concept up to its retirement. Taking it into account the systems engineering regards the LC management goal as the organization being able to choose and implement effective LC processes on a solid methodical basis. As a result, the system of the parts' interest can develop during its LC and satisfy the statutory requirements.

That is why systems engineering became the key compulsory subject for the future or present day engineers working for global engineering corporations as well as for the leading technical universities of the world.

Necessity of systems engineering education

For the last 10-15 years a set of theoretical and practical recommendations on complex systems development has been created and tested by international systems engineering associations. The formation of integrated international system of standards and the best practices is about to be finished. The practices contain the regulations and instructions to be used while developing a system and managing its LC. There are a lot of international corporations and organizations working on that problem. IEEE, INCOSE, Boeing Company, NASA, General Dynamics, BAE Systems and others are among them. The result of their activity is the formation of new cultural environment for developing a system of any class and purpose. The absolute majority of the successful companies, that develop competitive systems work in that environment. That process is taking place before our very eyes.

We can only bitterly state that our country hasn't taken practical part in formation of the environment. Besides, there are no specialists ready to use the systems engineering regulations and instructions while developing a system and managing its LC. Unfortunately no university trains such staff with the purpose to meet the demands of industry and society. Taking into account the mentioned above the necessity to establish systems engineering education both in the frame of Master and Bachelor degrees as well as in the frame of additional education becomes obvious.

The fact should be noticed that nowadays all over the world the companies

dealing with the complex system development feel the shortage of high qualified engineers. A lot of foreign experts including employers and higher school representatives declare the engineering education crisis which is conditioned by a number of factors. One of the factors is the fact that engineer's position doesn't bring any advantage. In particular, engineers are required high professional competencies but are low paid in comparison with lawyers, bank employees and government officials. Foreign colleges think that in these conditions high level of systems engineering education can not only contribute to the formation of common cultural engineering space but also encourage the young to choose engineering activities.

The interest of foreign scientific and educational community to systems engineering is proved by the facts that 50 manuals and textbooks on this topic have been published for the last 3 years and the subject of systems engineering and its sections are included in curricula of about 500 universities [9]. Teaching materials in systems engineering and its sections are widely presented in educational networks. MIT OpenCourseWare (http://ocw.mit.edu/index.htm) a site of Massachusetts Institute of Technology is an example. Finally, the biggest government agencies and the leading international enterprises are developing their own regulations in systems engineering [10, 11] and training their staff in this sphere [12, 13].

While discussing the problems of Russian engineering education reform we should determine the urgency to solve the problems of systems engineering as one of the key tasks. With systems engineering as a base it is possible for Russian Universities to train specialists who will be able to set goals and tasks, develop and manage competitive systems.

Who should organize (manage) systems engineering education?

To answer that question it is necessary to describe the domestic engineering environment. We should remind that the target training of systems engineers in our country was established quite long ago: systems engineering department was organized in Moscow Power Engineering Institute in 1969. Similar departments were gradually established in many technical higher schools all over the country and with the support of domestic industry in the mid 80s its number reached 30. Thus, the USSR industry jointly with higher education establishments made the conditions for training of systems engineers in quantity sufficient for the country. But the quantity didn't turn into quality. The domestic systems engineers were not the specialists to develop competitive systems; they couldn't formulate and define the scope of work to create a complex system, ensure the maintenance and management of its LC and use creatively technological, management and economical achievements in their work. Our engineer was trained primarily as a technical specialist who can solve the problems of development and functioning of automated process control systems and know how to make separate system elements.

There were a lot of factors conditioning such situation but we will mention only one: the original term "System engineering" being translated was substituted into "systemotekhnika", which was understood primarily as a technical term referring only to techniques and technology. The core of systems engineering as a cross discipline approach and methodic turned out to be lost to a large degree. During its infancy the USSR systems engineering didn't manage to integrate into the global systems engineering environment, which hindered its development. The events of the 80s and 90s put an end to it at all.

In addition to objective difficulties of engineering education and activities there is one more problem in our country: for the last 20 years we have lost a whole generation of system developing specialists on the one hand and the generation of instructors who could train engineers on modern basis on the other hand. This "lost generation" has no experience in big system development. The connection with real information holders in this sphere has been broken. This generation hasn't got basic fundamental training that can meet the demand of global modern technical development. Significant part of this generation even has no idea about the achievements of the world science and systems engineering. The language barrier adds to this problem: statistics show that most domestic specialists and graduates of the leading technical universities are not ready to work in English-speaking professional environment.

Russian engineering School and employers are disunited. It is quite common nowadays when large companies actually retrain their young engineers or hire foreign specialists. They consider it impractical to collaborate with higher school on a constant basis. Besides, experienced and high qualified specialists trained in the USSR are not psychologically ready to perceive modern foreign achievements because traditional engineering culture, inherited by us, and contemporary western engineering culture differ from each other greatly.

To overcome cultural differences is one of the key problems as we can keep and possibly develop our scientific potential in the sphere of competitive systems engineering only by integrating into the world engineering community. We should note that to overcome the cultural differences and the backlog the efforts only of higher School are not enough. The domestic industry should play an important part in it. It should take its place on the global market and form a clear image of what the national educational politics should be to have engineers able to create competitive systems.

Thus, great infrastructural shifts in domestic engineering environment are necessary to organize systems engineering education. Actually it is necessary to answer if our educational system is ready to become a part of the world educational system and if our domestic Higher School will be able to overcome the crisis of training of engineers who can make competitive products and services. On the other hand, our Higher School hasn't been answered yet if the domestic industry and business feel the shortage of such engineers or our country needs engineers to maintain foreign equipment and high qualified specialists are better to be trained abroad.

We should note that the collaboration of western universities with hi-tech producers is at a high level. For example, Massachusetts Institute of Technology, which is the leader of systems engineering education, collaborates with more than 20 world's largest companies in implementation of such educational programs. Among these companies there are Amazon.com, Inc; Boeing Company; Dell; Harley-Davidson; General Dynamics; General Motors; Honeywell; Intel; Nokia; Northrop Grumman; Novartis AG; Raytheon and this impressive list can be continued.

The problem solving in engineering education, in particular, systems engineering, is a common task both for domestic industry and higher school. The main problem, which is to ensure the possibility of stable development of solid domestic engineering environment for competitive complex system production, can be solved only by focused and concerted actions of all the interested parts. Systems engineering will only be a matter of enthusiasts unless higher institutions and the industry agree about engineers' training, unless the domestic industry integrates into the global engineering environment and offers the graduates decent working conditions, unless the engineering universities are aware of necessity to integrate into the world engineering education environment.

The reason for optimism is that the universities and the industry have started solving this problem.

In the end of 2010 the Department of Strategic Planning and Management Methodology was established in National Research Nuclear University MEPHI at the faculty of Physics and Economics of high technologies. The main aims of the department are to train engineers, architects and designers of LC of complex technological objects.

Some years ago a non-commercial organization – Russian Institute of Systems Engineering (RISE) – was established by a number of leading Moscow technical universities in close cooperation with the International Council on Systems Engineering (INCOSE). Its aim is the development of systems engineering in Russia.

In 2008–2011 a series of lectures, seminars and conferences conducted by the world leading specialists in systems engineering, LC management and data integration was held with a joint participation of RISE and All-Russian Research Institute for Nuclear Power Plant. Those events interested the engineering community very much and encouraged the launching of several innovative projects in the nuclear sector.

Approaches to education management in systems engineering

Foreign experience shows that it takes 6–8 years to train a component design engineer. And it takes 10–15 years to train a systems engineer who can develop system-wide solutions and do system integration.

To get a high professional level a systems engineer should have work experience in a world leading company of a particular direction. Thus, it is obvious that systems engineering training should take place on all educational level from bachelor degree up to the system of engineering further education.

While organizing systems engineering education it is useful to take into account foreign experience that shows that the first efforts should be focused on the following:

- to consolidate professional and academic societies that are interested in overcoming the crisis of engineering education in our country.
- to analyze and introduce advanced foreign experience in management of systems engineering education and systems engineer training.
- to choose pilot training lines to test the developed syllabi.
- to accelerate the formation of reference methodical and training materials in systems engineering available in Internet. The results of project BKCASE (Body of Knowledge and Curriculum to Advance Systems Engineering) can be taken as a basis. The project aims to form a set of knowledge and curriculum to advance systems engineering [14]. It is powered by Institute of Electrical and Electronics Engineers, IEEE, International Council in System Engineering, INCOSE, Association for Computing Machinery, ACM and many other world famous academic and professional organizations.
- to train instructors (teachers) in systems engineering and related subjects in leading foreign universities with the help of Russian industry and professional organizations.
- to translate into Russian a set of the best foreign textbooks and books for systems engineering like it was done in the USSR in the 60's of the last century on the initiative of Professor Povarov G.N.

The problems of academic and professional communities' consolidation were mentioned above.

While studying foreign experience of educational program management we notice two problems stated by our colleges: the choice of key competences required from a system design-engineer and the formation of basic requirements to the content of educational programs. The example is the work of 15 employees of National Space Agency of the USA that have all together 390 years of collective experience (almost 4 centuries) in systems engineering in aerospace section [15].

These specialists distinguish 11 basic personal qualities for a good systems engineer to have:

1. Intellectual curiosity which is expressed through the willingness and ability to constant learning of new.

2. The ability to see the whole even if there are a lot of small details. In particular, the ability to keep in mind the main goal and to unite scientists, designers, operators and other interested parts for effective collaboration regardless the changes appearing during the LC.

3. The ability to distinguish the system-wide connections and regularities, which makes the system engineer being able to help other team members to put their system solutions in the whole system to get the system's goals.

4. High sociability. That is the ability to listen, to write and to speak in the manner that helps (promotes) effective communication between engineers and managers on the basis of common terms, processes and procedures.

5. The ability to work both as a leader and as a team member, which implies deep interdisciplinary knowledge, being target driven, creativity and engineering instinct.

6. Readiness for changes including the awareness of their inevitability.

7. Suitability to work in conditions of uncertainty and lack of information, which implies the ability to interpret contradictory and incomplete requirements.

8. Conviction that you should hope for the best but plan to worst, which means that a systems engineer always check and check again the details referring to the system technical integrity.

9. Different technical skills - the ability to use reasonable technical solutions, which requires expert interdisciplinary knowledge.

10. Self-confidence and determination but not arrogance as any system engineer can make a mistake.

11. The ability to follow the instruction up to the moment when it is necessary

to change it, which implies engineering instinct.

On the other hand, there are more detailed descriptions of the requirements for system engineers [16]:

1. The ability to manage the requirements on all the levels of system's hierarchy.
2. The ability to use advanced methods and instruments of system development including architecture approach.
3. The ability to use methods and instruments of system analysis including modeling, reliability analysis, risk analysis, analysis of the technical and economic characteristics etc.
4. The ability to organize and conduct system's test and to analyze test data.
5. The ability to organize human-machine interaction.
6. The ability to implement integrated system solutions taking into account heterogeneity and the possible distribution of system elements.
7. The skill to implement the process approach.
8. The skill to manage changes.

Considering the issue we can analyze the basic standards of systems and program engineering [17, 18], the international organizations' recommendations [6] and the author's recommendations (for example [7]). It is also possible to give general characteristics of the typical profile of a systems engineer's activity and that of a contemporary engineering specialist (Fig. 1).

As shown in Figure, the systems engineer's basic efforts are focused on technical and design activities and besides design activity includes both works on system project management and works on configuration and risk management, taking decisions, measurements etc. On the other hand, in the process of system developing one thirds of systems engineer's efforts are spent on management and agreement activities. Typical processes that a systems engineer has to deal with at different LC stages are shown in Table 1.

It is interesting to compare the profiles mentioned above with some competences the engineering graduates (bachelors, masters and specialists) should have according to SES 3 (Table 2). These data need to be specially and deeply analyzed but even at the preliminary examination it is obvious that there is no system in the formation of competence profiles for engineering bachelors and masters. The same fact is true for the engineering specialists trained in accordance with SES 3.

The idea is that while choosing pilot directions it is necessary to start with establishing effective retraining and further training system for systems engineering stuff. This process should start with training of professional teachers (instructors) in systems engineering. Taking into account the immensity and multidimensionality of the problem it can't be expected to be solved in the near future at the state level. Apparently, to solve the problem one should rely on help of corporations that are interested in producing competitive complex systems to take a share of the world market. The experience of Public Corporation "Rosatom" might be interesting in this aspect. Since 2008 its enterprises have been implementing the recommendation of basic international standards of LC systems management ISO/IEC 15288 and informational support of LC ISO 15926 in their engineering activities.

While forming reference training materials in systems engineering available in Internet it is necessary to consider systems engineering and the related subjects as the basic ones for implementing the curriculum for designers of complex systems. Besides, we think that the Russian Association for Engineering Education and the Association of Technical Universities of Russia could support the prompt publication of BKCASE project's methodical materials in the Russian language and its further discussion by academic public of engineering universities of the country.

As for the retraining of domestic instructors and publishing of the best foreign books in systems engineering in Russian, this work has been started by RISE.

Lastly, it is necessary to note that while developing the systems engineering curriculum and the curricula of the related subjects it is necessary to look to the integration of Russian Higher School into the world community of system designers, to fast acquisition of the world scientific and engineering achievements and to effective adaptation of foreign programs and methods to our conditions. Above all, this topic needs to be studied and considered in details in academic, university and trade journals due to its big value and volume.

Fig. 1 Approximate activity profile of a system engineer (a) and contemporary engineering specialist (b)

Fig. 1 a)

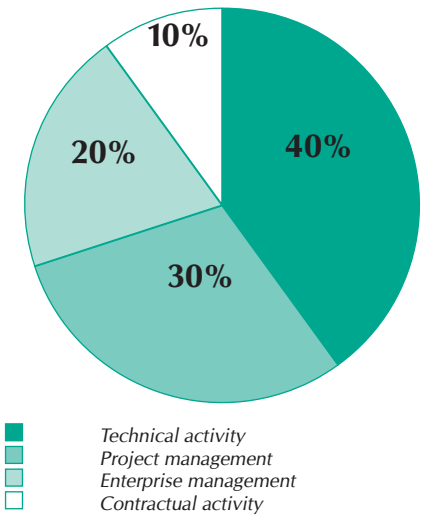
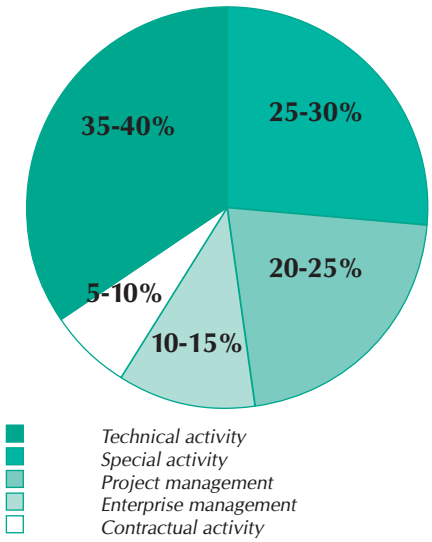


Fig. 1b)



Conclusion

The lack of attention to the organization and practical realization of system engineering education, the problem of "lost generation" of system designers, the need to take into account cultural differences between the rapidly developing western school and aging domestic school of system developments are a great challenge for our higher engineering school.

To find the way out of the situation it is necessary to integrate deeply the Russian engineering higher school into the world community of systems designers, to master the world practical and scientific achievements in systems engineering and to include systems engineering and the related subjects into the bachelor's, specialist's and master's engineering curricula. We should also purposefully adopt the extant domestic methods and traditions of complex system development to the system development methodology acknowledged by the international community.

The system movement becomes of high importance. It unites all the interested

Table 1
Systems Engineering standard covering processes and life cycle stages according to ISO/IEC 15288

Project-enabling processes	Project processes	Technical Processes
LC model management Infrastructure management Project portfolio management Human resource management Quality management	Project planning Project assess and control Decision management Risk management Configuration management Information management Measurement	1. Stakeholder Requirements Definition Process 2. Requirements Analysis Process 3. Architectural Design Process 4. Implementation Process 5. Integration Process 6. Verification Process 7. Transition Process 8. Validation Process 9. Operation Process 10. Maintenance Process 11. Disposal Process
Agreement processes		
Acquisition Supply		

parts such as teachers, specialists, students and post-graduates and can significantly contribute to the formation and possible development of modern educational environment which is suitable for systems engineers training and retraining in our country. It becomes more important taking into account the fact that we will hardly have this formation driven from top-down.

We think that the training in systems engineering is an important tool for creating new generation of engineers who are ready to produce competitive systems. It is a tool suitable for answering the challenges and for solving a number of problems facing engineering education and Russian engineering nowadays.

Table 2

Training direction	professional competences (types of activities) according to Russian SES 3								
	total	general	research	management	design	service and operation	installation and adjustment	industry and technology	other
	Bachelor (Master) degree								
140400 Electricity and Electrical Engineering	51 (32)	7 (9)	8 (3)	10 (7)	10 (6)	4 (0)	2 (0)	10 (6)	0 (1) (pedagogical)
140700 Nuclear Power and Thermal Physics	19 (28)	7 (9)	3 (5)	3 (6)	3 (4)	0 (0)	3 (0)	0 (0)	0 (4) (pedagogical)
141100 Power engineering	24 (22)	7 (9)	2 (4)	3 (2)	6 (4)	4 (united) (1)		2 (1)	1 (0) (pedagogical)
150700 Mechanical Engineering	26 (26)	0 (0)	4 (4)	8 (13)	6 (4)	0 (0)	0 (0)	8 (5)	0 (0)
160100 Aircraft	21 (23)	0 (0)	0 (7)	4 (7)	11 (5)	0 (0)	0 (0)	6 (0)	0 (4) (design and technology)
180100 Shipbuilding	19 (29)	0 (0)	4 (7)	5 (9)	3 (4)	2 (5) (technical and operational)	0 (0)	5 (4)	0 (0)
200100 Instrumentation	33 (31)	8 (6)	6 (6)	6 (6)	6 (8)	0 (0)	0 (0)	7 (5)	0 (0)
210400 Radio Engineering	32 (27)	7 (6)	5 (5)	4 (5)	5 (4)	4 (0)	2 (0)	5 (0)	1 (5) 0 (2) (design and technology, science and pedagogical)
220100 Systems Analyses and Management	13 (13)	7 (6)	2 (1)	0 (0)	4 (3)	0 (0)	0 (0)	0 (0)	2 (2) 0 (1) (science and pedagogical, design and technology)
231000 Program Engineering	27 (17)	0 (0)	5 (3)	4 (3)	6 (3)	2 (1)	0 (0)	2 (1) (technological), 3 (1) (industry)	3 (2) (аналитическая), 2 (3) (pedagogical)
the average bachelor (master)	26 (26)	4 (4)	3 (5)	5 (6)	6 (5)	1 (1)	1 (0)	5 (3)	1 (2)

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