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Interdisciplinary competencies of managers for a technological breakthrough

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Abstract

The article aims to study the structure of and improve the model for the fostering of managerial competencies to solve the problems of a technological breakthrough in the domestic economy. The authors apply their proprietary approach that makes it possible to reveal the range of interdisciplinarity and to specify its content. Methods and tools for mastering the competencies in demand are developed. As the empirical base which proves the validity of their conclusions, the authors cite their own research as well as the results of the analysis of educational programs in engineering management implemented at the leading universities of the world, and the expert opinions of the heads of energy enterprises and professors of Russian universities. The paper analyzes the key factors in the formation of interdisciplinary competencies: a management paradigm towards which the educational process is oriented, a model of knowledge and skills that is adequate to the content of the tasks of a technological breakthrough, a methodology for analyzing interdisciplinary relationships in managerial decisions. The article outlines the relevant experience of training managers of various levels by the Department of Energy Management Systems and Industrial Enterprises of Ural Federal University.

The study is scientifically novel as it discovers a new approach to understanding interdisciplinarity when determining the managerial competencies necessary for a technological breakthrough. The practical significance of the article is due to the fact that it presents the experience of implementing the developed approach to the training of managers with an increased readiness to constantly embrace and implement future technologies.

Keywords: interdisciplinarity, interdisciplinary competencies, technological breakthrough, managerial education, proactive management, advanced learning, systems engineering, methodology for training managers.

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Introduction

The issue of applying an interdisciplinary approach in science, education, and practice has gained particular popularity over the past decade, characteried by an intense flow of technological innovations, an ever-increasing uncertainty of the context, and profound changes in political, economic and social foundations.

Interdisciplinarity, as noted in [Arbesman, 2015], is today found in almost everything. Of course, this trend can be considered a manifestation of academic fashion. However, if we look at the number of publications with the keywords "interdisciplinarity" or "interdisciplinary" in the scientific bases of the peer-reviewed literature from 2010 to 2021, it seems possible to clearly record the steady positive dynamics of the interest of authors and readers in this phenomenon (Fig. 1). It can be safely assumed that the trend towards interdisciplinarity will further intensify as the volume of new complex tasks grows, as knowledge differentiation and integration increases [Kodama, 2018].

By interdisciplinarity the authors understand the synthesis of knowledge from different fields of science and practice and the identification of new relationships between them, which make it possible to obtain qualitatively new solutions to complex problems. It is important to pay attention to the practical significance of this interpretation: due to the interdisciplinarity, it becomes possible to generate knowledge, without which it is virtually impossible to solve problems with a nonlinear, unclear structure in conditions of continuous change, uncertainty, and chaos. This statement is of particular relevance when aiming for a technological breakthrough, when it is necessary to create and quickly implement unique innovations simultaneously in a wide variety of industries and processes. Due to the mutual enrichment of scientific disciplines or areas of practical activity, completely new questions are identified and problems are formulated, the research results of which allow to obtain methodological tools, expand the horizon of science and increase the efficiency of practice.

In such axiomatics, a specialist, be it an engineer, a manager, an expert in information technology, must quickly navigate even in those areas of knowledge, markets and industries that were traditionally not “mandatory” for his field of activity. The scale, depth, and versatility of the expertise of a new generation professional are increasing dramatically today, which requires reflection in educational programs of different areas of training. Speaking about management education in particular, when training managers, it is important not only to demonstrate the possibilities of interdisciplinary methodology as a way to organise teamwork for a comprehensive analysis of the situation and improve heuristic efficiency, but also to equip them with an arsenal of appropriate decision-making tools [Chryssolouris et al., 2013; Carr et al., 2018; Gitelman et al., 2019; Professionals in competition.., 2021].

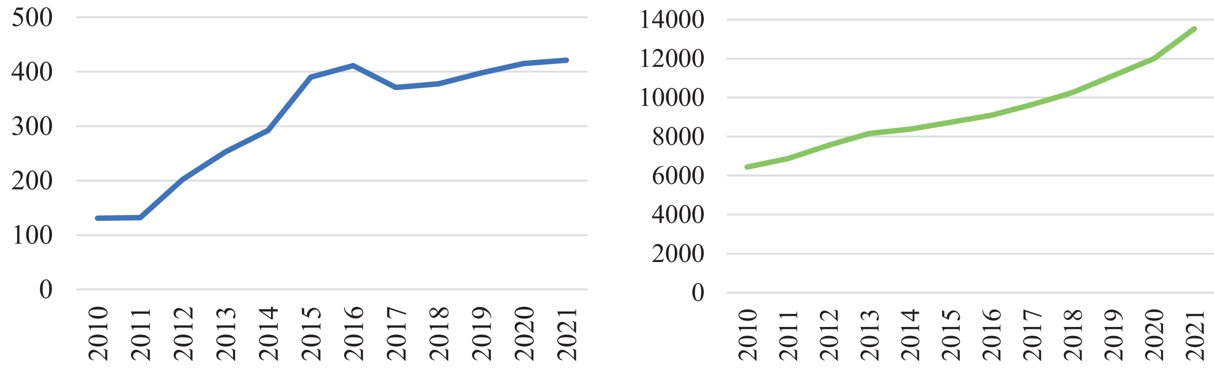
The purpose of this article is to identify the forms of interdisciplinarity and interdisciplinary competencies of managers that are especially significant for a technological breakthrough and to determine the most effective ways to form them. The author's approach to the definition of interdisciplinarity made it possible to identify the composition of the necessary interdisciplinary competencies and their relationship, which is important to take into account in the training of innovative managers.

1. Model of interdisciplinary competencies of managers for a technological breakthrough

The reduction of the "half-life" of professional knowledge and the avalanche-like growth in the volume of new information necessary for professional activity, on the one hand, and the limited time frame for the formation of new competencies, on the other, require constant analysis and restructuring of the conceptual model of competencies required in solving actual and predictable tasks. The growing complexity of tasks and the environment of managerial activity leads to the fact that instead of obsolete competencies, there is a need for modernised or completely new ones, which are characterised by a more interdisciplinary content and, accordingly, a more labor-intensive process of their formation.

Under the conceptual model of competencies, the authors mean the composition of clusters and the content of specific competencies included in them, integrated into a single system in accordance with their interrelations and dependencies and reflecting the ability of a professional to solve a certain class of tasks and problems. Such a system of competencies is a model of an educational program graduate, which determines the goals, requirements for the content and methodological organisation

Fig. 1. Dynamics of the number of publications containing the keywords “interdisciplinarity” and “interdisciplinary” in bibliographic databases:
a) in the Russian eLibrary database, b) in the international SCOPUS database



a) b)

of the educational process. The model should have a simple and illustrative form, convenient, readable and accessible for analysis and conclusions. At the same time, the first step in the transition from the model of a specialist to the process of its formation is the selection and full description of the complex of tasks that he must solve in his professional activity.

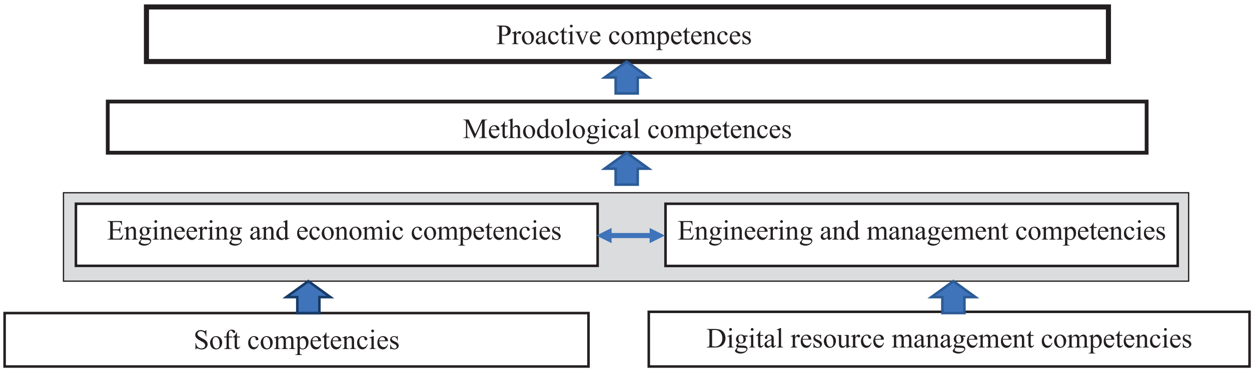
The structure and content of the conceptual model of actual competencies are determined by the management paradigm that the educational process is focused on in accordance with the understanding of the practical requirements for graduates of the management training program. Thus, the process of preparing a manager begins with the choice of a management paradigm and the development of a competency-based model of managerial activity corresponding to it.

The proactive control paradigm is the most appropriate for the tasks of a technological breakthrough. It determines not only the composition of competencies, but also their relationship and subordination, which are important to consider in the process of their formation. For this paradigm and, accordingly, a technological breakthrough, a suitable model is that includes the following clusters of managerial competencies: proactive competencies, methodological competencies, engineering

Table 1
The structure of interdisciplinary competencies of managers

Cluster competencies	Examples of specific competencies
Proactive measures	• Creation of systems for early detection of threats and opportunities • Concept design • Visual analytics • Designing the future of the company • Development of leadership strategies • Organisation of advanced training
Methodological	• Selection of tools for solving new problems, taking into account their interdisciplinary specifics • Development of integrated solutions at the intersection of management, engineering, economics, IT technologies, ecology, psychology, sociology • Conceptualisation of new scientific knowledge and technologies in the development of innovative projects • Assessment of the need to update their professional competencies in accordance with new interdisciplinary knowledge
Engineering-economical	• Economic evaluation of engineering solutions • Comprehensive analytics for solving breakthrough problems • Management accounting in interdisciplinary projects • Economic calculations and advanced business development models • Investment management in innovation engineering • Estimating costs and predicting the results of large projects • Assessing risks and resource efficiency
Engineering-management	• Organisation of technological modernisation processes • Project portfolio management • Support for technological entrepreneurship • Managing the interaction of employees, contractors, developers in solving complex problems • Organisation of network cooperation and distributed leadership
Digital resource management	• Digital remote control instruments • Application of Internet technologies in organisational activities • Technologies for the use of smart systems • Organisation of business processes in a virtual environment • Conceptualisation of technological process digitalisation
Soft skills	• Social, cross-cultural and interpersonal communications • Ability to collaborate productively and work as a team in a digital environment • Ability for self-development, self-learning and self-regulation • Ability to adapt and achieve results in a changing environment

Fig. 2. The logic of the formation of managerial competencies for a technological breakthrough in accordance with the subordination of their content



and managerial competencies, engineering and economic competencies, digital resource management competencies, soft competencies [Gitelman et al., 2020b].

This sequential list of competency clusters is a hierarchical structure, in which each of the clusters includes managerial abilities contained in the competencies below (Table 1).

In accordance with the understanding of the subordination and interrelationships of the main competencies of managers who are able to work in the proactive management paradigm, the optimal logic of their formation in training is determined (Fig. 2).

All these competencies are formed on the basis and to a large extent in the process of fundamental training, which creates a scientific understanding of the tasks and possibilities for their solution. Fundamental knowledge is the basis for the formation of interdisciplinary competencies, and the flexibility of thinking ensures the quality and dynamics of this process [Gitelman et al., 2022]. In turn, the formed interdisciplinary competencies develop the flexibility of managerial thinking and consolidate fundamental knowledge. Thus, the formation of abilities to solve interdisciplinary problems is closely related to the fundamental knowledge and flexibility of managerial thinking.

Let us give a generalised description of competence clusters discussed above.

Proactive competencies - the ability to anticipate changes in many heterogeneous factors, events and contexts, predict the future of the organisation and, based on this, develop solutions and proactive actions to adapt systems and business processes to anticipated and unpredictable changes.

In the competencies of preventive actions, research is highlighted, defined as the ability to see the need for additional study of certain issues and conditions of organisational and managerial activity, set specific tasks for applied research and organise its conduct, use the results obtained to make decisions, taking into account possible changes in the internal and external environment of the organisation.

Methodological competencies, as well as research competencies, acquire high significance with proactive management and organisation of advanced learning. They are abilities that allow you to develop a new vision and restructure your activities in connection with the emergence of fundamental changes in organisational systems. Theoretical training, flexible intellectual models and adaptive individual managerial strategies are necessary conditions for the formation of methodological competencies, which:

- expand the range of interdisciplinarity and the arsenal of systemic actions required to solve new complex problems;
- provide integrated solutions at the intersection of management, engineering, economics, IT-technologies, ecology, psychology, sociology and other scientific fields;
- establish and use the relationship between existing experience and new areas of activity, as well as new professions that become necessary to solve innovative problems.

Engineering and economic competencies (EEC) - the ability to use economic knowledge in evaluating the effectiveness of creating new technical and technological systems and their operation. The possession of these competencies is an indispensable condition for the work of a leader in order to make decisions regarding innovative activities.

Engineering and management competencies (EMC) - the ability to organise an active innovation process, the necessary organisational changes and the appropriate corporate culture, manage the life cycle of technological systems, improve internal and external communications, work with personnel (selection, motivation, professional growth and development of abilities), determine the priorities for the allocation of resources, taking into account the interests of stakeholders.

Unfortunately, in foreign publications, almost no attention is paid to the problems of the formation of EEC and EMC. The fact that managers need to know the basics of engineering and economics, as well as the fact that engineers need to master individual management tools, be able to work in project teams and understand the logic of entrepreneurship, seems indisputable today. With a deeper literary analysis, it turns out that specific tools for mastering the engineering and economic competencies of managers, their composition, and the required educational content are described very superficially.

Nevertheless, some generalisations regarding other views on the interpretation of these types of competencies can be made. So, EEC, as a rule, is understood as technical literacy, which is expressed in various attributes: the ability to "speak the same language" with engineering personnel, read the simplest diagrams and drawings, understand the composition and structure of the equipment of production systems, and, ultimately, based on this knowledge determine the economic component of certain engineering solutions [Childs, Gibson, 2009; Barrett, 2020; Klinbumrung, 2020]. The objective function of the EEC is formulated in [El-Baz, El-Sayegh, 2007] and is to help managers "expand" the production cycle into separate stages, evaluate the cost and predict the contribution of each of them to the overall financial result of the company.

As for EMC, they are a "consequence" of EEC and, according to a number of authors [Panuwatwanich et al., 2011; Pons, 2015; Jamieson, Donald, 2020], include a variety of decision-making skills regarding business development, taking into account the impact of the technological factor on the company's economy, its organisational structure, and market behavior model. Thus, EEC (first level competencies) only allow estimating the cost of certain production solutions, converting engineering developments, prototypes, rationalisation proposals into money, and EEC (next level competencies) provide an opportunity to create deeper projects of business transformations based on such an engineering and economic assessment.

The results of our research [Gitelman et al., 2020a; Gitelman et al., 2020b; Professionals in competition.., 2021] demonstrate a greatly increased importance in the management of complex production systems of EEC and EMC, which are based on knowledge of the latest technologies and their

Fig. 3. Taxonomy of basic digital competencies of managers

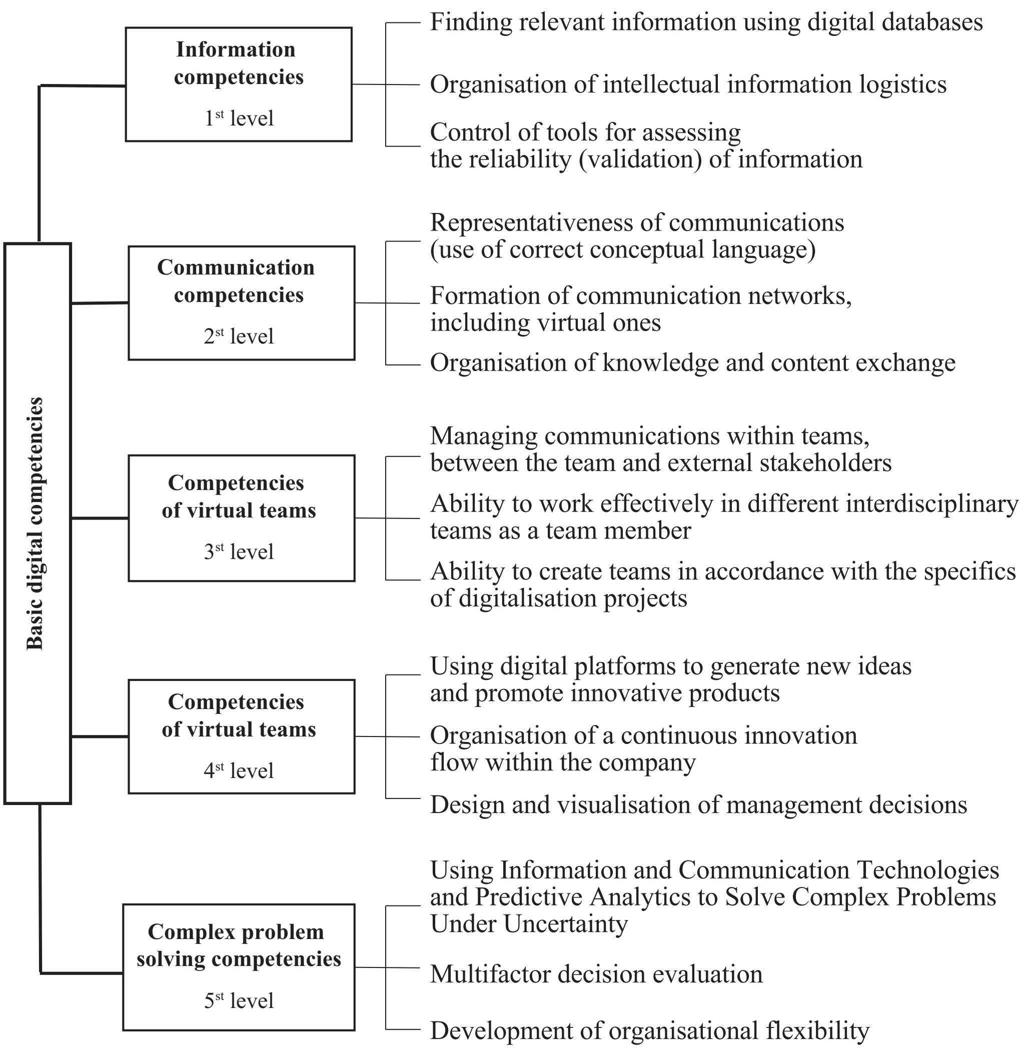
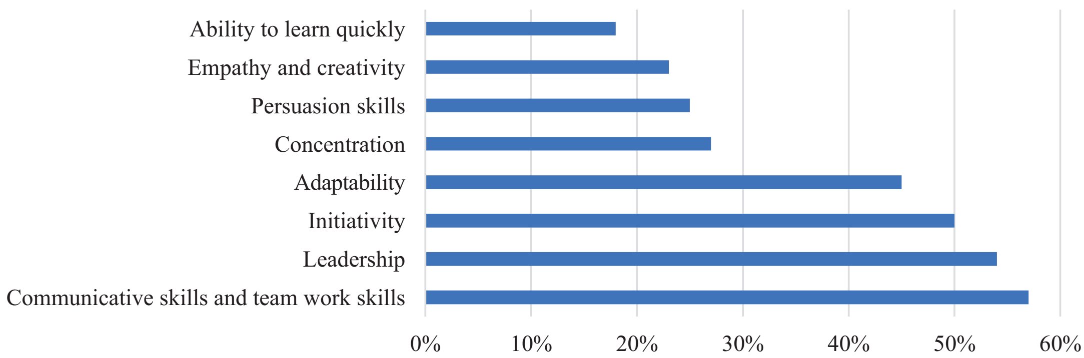


Fig. 4. The main soft skills of managers



Source: compiled by the authors based on [Training digital skills.., 2018; Apostolopoulos, 2020].

impact on the organisation of activities, business models, assessment of efficiency and risks, requirements for personnel. These competencies acquire particular importance during digitalisation: without mastering them, the manager will not be able to set specific substantive tasks for specialists.

Digital resource management competencies (manager's digital competencies) - the ability to work with complex information systems, large data sets and artificial intelligence, as well as rebuild business processes and organisational systems based on taking into account and using the capabilities of cloud technologies, the Internet of things, self-learning robotic complexes and smart environments.

Determining the content and structure of digital competencies is a highly relevant topic on the international research agenda [Van Laar et al., 2019; Oberlander et al., 2020; Van Laar et al., 2020]. In particular, E. Van Laar and colleagues [Van Laar et al., 2019; Van Laar et al., 2020] is attempting to create a taxonomy of digital competencies that includes five levels. The developers of the taxonomy assume that, without having mastered the first level competencies, it is impossible to fully master the second level competencies, and so on. (Fig. 3).

Digital competencies are based on digital skills - well-established behaviors brought to automatism based on knowledge and skills in the use of digital devices, communication applications and virtual networks [Training digital skills.., 2018].

Soft competencies (universal, soft skills) - the ability to act, carry out introspection and solve problems, taking into account the personal qualities of partners, the social environment, group and interpersonal interactions, which are similar in many areas and fields of activity. According to the results of a survey conducted by the developer of educational services Talent

Fig. 5. STEM concept in education

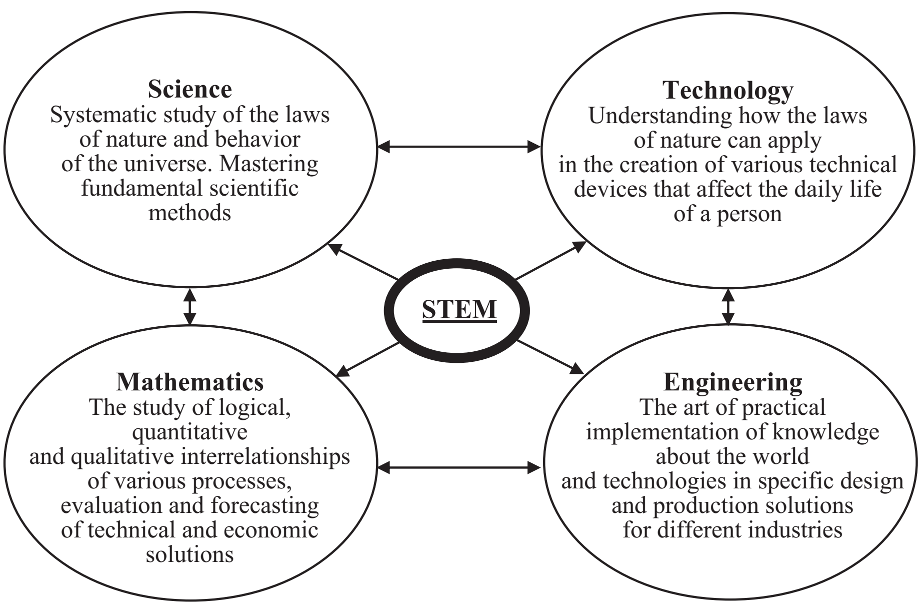


Table 2
Annual master’s program in management in engineering from Duke University (USA)

Subjects	1st term	2nd term
Basic	Marketing Finance in the high-tech industry	Intellectual Property, Business Law and Entrepreneurship Management in the high-tech industry
Elective courses (4 at option)	Product development management Commercialisation of high-tech innovations Operations management Quantitative financial analysis Design thinking Customer Experience Design Artificial intelligence in action Marketing, analytics and research Data search and analytics Real-time data technologies Fundamentals of Data Science Fundamentals of Software Management (SW) Software Quality Management Competitive Strategies I Industrial Consulting Practice I Project Management I Management Decision Models I	Negotiations and sales Advanced finance for knowledge-intensive business Supply chain management Innovation management What's New in Big Data Analytics Data visualisation Principles and Applications of Machine Learning Intelligent Asset Management Uncertainty design and decision optimisation Product design Engineering Entrepreneurship Competitive Strategies II Industrial Consulting Practice II Project Management II Management decision models II

Table 3
Master’s program “Management and engineering in the power industry” from
University of Aachen (Germany) + Maastricht Business School (The Netherlands)

1st term (Aachen)	Electrical Machines I Testing and diagnostics in complex systems engineering Energy transformations: fundamentals, topology, analytical tools Electricity storage and accumulation systems Entrepreneurial strategy Technological development strategy	2nd term (Aachen)	Electrical machines II High-voltage equipment in main and distribution electrical networks Automation in complex power systems Accidents and resilience of power systems Energy economics in the context of liberalised energy markets Finance and accounting (controlling) Electricity storage and accumulation systems - laboratory practice
3rd term (Maastricht Business School)	Global trends and sustainable business competitiveness Organisational development and transformation Management of international network projects business economics Responsible Supply Chain Management Human capital management	4th term (Aachen or Maastricht Business School)	Master's thesis preparation

LMS, soft competencies were identified that most employees of the surveyed companies need to develop (Fig. 4).

Of the soft competencies, one should single out the ability for teamwork, which every year is becoming an increasingly important and necessary element of a manager's professionalism, especially when solving the problems of technological modernisation and digital transformation of a business.

2. At the center of the current agenda are engineering-economic and engineering-management competencies

An analysis of world practice shows that these competencies are formed in conjunction in special programs in engineering management (Engineering Management), as a rule, implemented in the magistracy (although there are examples of both bachelor's and MBA programs in this area, and also a combination of a master's degree and MBA, as is done at Harvard University [MS/MBA: Engineering sciences, w.y.; Top 9 stem-certified.., w.y.]). The standard requirement for applicants to a master's program is a basic education in the STEM model (science, technology, engineering and mathematics) [Masters in engineering management.., 2021].

STEM refers to the concept of interdisciplinary problem-based learning that involves students in activities related to the design, development and operation of technological systems; open, case-oriented discussions on topical issues from the world of science, technology, social sphere; solving problems of specific industries and companies based on the application of fundamental knowledge about nature and the laws of technological development; team and individual work to solve problems of high uncertainty [White, 2014; Zaher, Damaj, 2018; Application trends.., 2019].

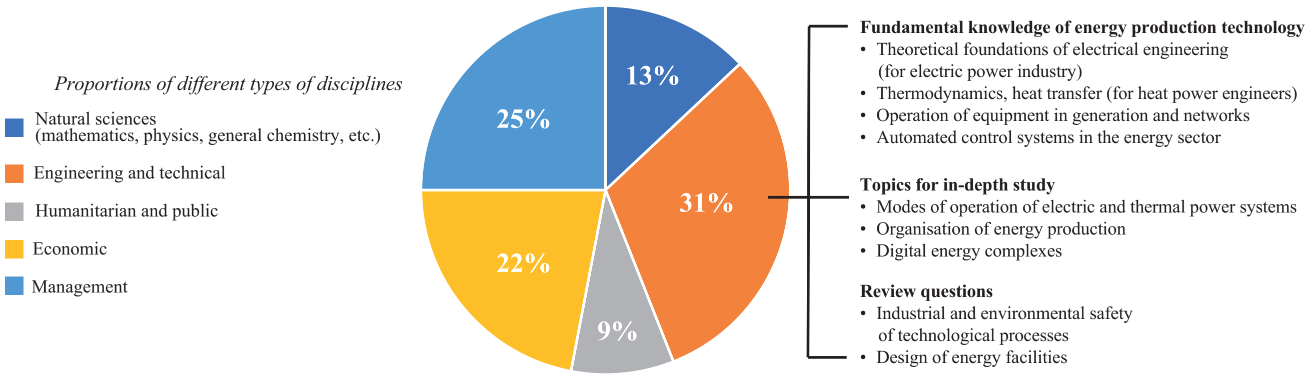
All elements of the concept are closely interconnected and organically complement each other. The semantic roles played by each of the elements in the educational process are shown in Fig. 5.

As the object of study becomes more complex and the qualifications of students grow, the proportions of STEM shift towards an increase in the Technology and Engineering elements [Application trends.., 2019]. In other words, the more complex the issues discussed and the more qualified the audience, the

Table 4
“System design and management” course examples (MIT)

Course type	Engineering	Management	Interdisciplinary
Basic	System analysis Computer systems design principles Statistics for engineers and research specialists Operations engineering	Strategic innovation management and entrepreneurship Introduction to operations management Competition in an unstable environment Economic analysis for decision making	—
Advanced study	Engineering of human-machine systems of business Engineering of distributed computer systems Resource support for production: energy, materials, processes Optimisation of logistics systems	Strategy for anticipating market changes Theory and practice of behavioral decisions Power and negotiations Business analysis Investment management Innovative business ecosystems	Manufacturing systems Design of logistics systems Risk based solutions
Elective courses	Sustainable energy in the context of climate change Biomaterials engineering Aerospace systems engineering Software engineering Systems engineering (Advanced) Cyber security Cognitive robotics Integrated microelectronics Materials engineering for clean energy Robotics	Strategic opportunities in energy Transformation of business models in the digital economy Financial data analysis and programming Leadership in uncertainty Data-driven communications Blockchain in business Game theory for competition for the future	Creative leadership teams Engineering, economics and regulation in the electric power industry Data analysis to create new value Innovation teams Business systems architecture Roadmaps for technological business development

Fig. 6. "Reference" structure of the educational program for training energy managers



Source: Compiled by the authors based on the results of a questionnaire survey.

fewer hours in the curriculum are devoted to fundamental laws and applied methods.

An analysis of the curricula of Master's programs in Engineering Management, implemented at the world's leading universities (included in the top 100 international rankings QS and THE), allows us to distinguish three types of them.

1. Programs aimed at universal training of leaders. They include an average of 10-15 courses in the field of production, operational, IT management, sometimes with a focus on advanced technologies of the industrial revolution. The courses studied can be conditionally divided into two blocks: traditional (finance and economics, accounting, quality management, personnel management, operational management) and interdisciplinary with a focus on the technological aspect of business (systems engineering, development of innovations in engineering and management, information and analytical systems, business modeling, project management for the development of production and business) [Mesquita et al., 2015]. An example of a program of this type is shown in Table. 2.

2. Leadership training programs for specific industries with advanced technologies that play a significant role in the functioning and development of a business. The corresponding example is given in Table. 3.

3. Advanced programs focused on training innovative managers prepared for continuous development, testing and implementation of future technologies in engineering, IT, environmental security sector.

As examples of programs of the third type, we cite Stanford University (USA) and the Massachusetts Institute of Technology (USA).

The Management and Engineering program at Stanford University is built around six research topics that are directly integrated into the curriculum content at both the undergraduate and graduate levels: Computational Social Science, Decision Making and Risk Analysis, Operations Research, Organisational Management, Technology and Entrepreneurship, policy and strategy, quantitative methods of financial analysis. Among the main learning outcomes of the program: mastery of the mathematical apparatus, the ability to plan and conduct experiments, the ability to design complex systems (based on systems engineering tools).

At MIT, the Systems Design and Management program is built on the three-orbit principle. On the central orbit - basic courses in engineering and management (36 credits). On the second orbit - compulsory courses of in-depth study (in the amount of 12 credits in engineering + 12 credits in management). And, finally, on the third orbit - elective courses at the student's choice (Table 4). Students are required to earn a minimum of 30 credits, with a choice of engineering, management and interdisciplinary courses. The list of electives to choose from is significant: approximately 150 courses in engineering, 50 management and 30 interdisciplinary courses.

The practice of leading universities demonstrates an increased interest in engineering management, engineering and economic education. This is no coincidence: the production of the future, industry 4.0, is increasingly being put at the forefront. In Russian universities focused on complex high-tech industries (MEPhI, MAI, Moscow State Technical University named after N.E. Bauman, ITMO University and others), these issues are also given increasing attention when training managers and economists.

In complex high-tech industries, EEC are key competencies, since they ensure the functioning and development of the enterprise, its technical, technological and economic systems as a whole from the standpoint of improving reliability, safety, environmental and economic efficiency. EECs are in demand in substantiating and making managerial decisions in almost all areas of activity (logistics, finance, marketing, strategic management, etc.).

For example, in the power industry, as part of the fuel supply process at power plants, it is necessary to understand that the boiler runs on fuel of a certain quality, has strictly specific suppliers and prices. In financial activities, when planning

Таблица 5
Междисциплинарные взаимосвязи энергетического перехода
Table 5
Interdisciplinary relationships of the energy transition

Links	Subject of management decision making (examples)
Technology - economy	Electricity prices - a methodology for assessing indicators of the effectiveness of capital investments
Economy-technology	Technical and economic indicators of power plants - issues of reliability management, optimisation of power system modes
Technology-ecology	Various forms of environmental impact of power equipment
Ecology-technology	Ecological decision-making criterion in managing the development and operation of the electric power industry
Ecology-economy	Environmental payments - current costs in environmental protection equipment
Economy-ecology	Economic constraints, such as doubling prices to lower environmental regulations (compromise target)
Economy-society	The impact of electricity and heating prices on people's living standards and their satisfaction with energy policy
Ecology - residents of the region	The impact of the environment determined by energy equipment on the health of the inhabitants of the region

the budget of an energy company, it is necessary to know the relationship between the efficiency of power units and business results. Energy marketing involves rational behavior in the energy and capacity market of an active consumer - a customer of the energy system for the necessary services. It is not without reason that our survey of experts revealed the special importance of engineering and technical disciplines in the preparation of energy managers: according to the respondents, it is precisely such disciplines, organically interconnected with economic and managerial ones, that come to the fore in training and should occupy more than 30% of the teaching load (Fig. 6).

The problem of a shortage of specialists with EEC is significantly aggravated if it is considered in the context of scientific and technological progress on the side of electricity consumers - at a new stage of electrification, a characteristic feature of which is the integration of intelligent energy systems and power-consuming systems into single self-adjusting and self-regulating production complexes. Important effects of this electrification stage are structural and market: the emergence of new jobs and professions, the development of new markets and related technologies. For example, in transport, due to the advent of high-speed railways and smart automotive infrastructure, an explosive demand is expected in the next 5–7 years for chemists, scientists in the field of new materials, software engineers, industrial designers, urban economists, and service systems designers [Creating the clean energy.., 2013; Technology outlook 2025.., 2016].

In general, it can be noted that the trends of further changes in EEC specialists in the electric power industry are associated with a number of factors:

1) development of energy markets and increased competition;
2) introduction of intelligent energy systems;
3) business diversification and development of economic relations between energy suppliers and consumers.

3. Systems engineering as a methodology for using interdisciplinary relationships in management decisions.

An understanding of interdisciplinary relationships is especially required for managers of industries that are the most complex engineering and technical complexes, such as the electric power industry, the telecommunications sector, the nuclear and oil and gas industries, transport, and the military space sector. In these sectors, they are technologies in the broadest sense, from targeted research and engineering to innovation, that are the objects of concentration of interdisciplinary relationships [Schoemaker et al., 2013; Okhtilev et al., 2014]. Therefore, knowledge of the engineering foundations of production and scientific and technological trends is an indispensable condition for the ability of a manager to perform his functions successfully. Therefore, in management education, the volume and content of scientific and technical, engineering and technological, technical and economic training should be significantly strengthened, which will allow the manager to master the connections between technology, economics, ecology, the human factor [Gitelman et al., 2017], link professional knowledge with unique industry specifics.

Let us explain this thesis on the example of energy transition problem, which is extremely relevant for modern society - the movement of energy, related infrastructures and energy-consuming systems to a carbon-neutral model, implemented on the basis of structural and technological transformations that have environmental, economic and technological results.

Already from the very definition of the energy transition follows the objective need to identify the relationship between the technique and technology of energy production, energy economics, and environmental aspects of energy production (Table 5). In particular, we are talking about strengthening and new forms of technical and economic ties in the “supplier-consumer” aspect, including the quality and reliability of energy supply. Each of these relationships requires specific interdisciplinary competencies.

As a result of taking into account these interdisciplinary relationships, it is possible to develop integrated solutions that, in terms of content, are focused on:

- a comprehensive assessment of the results and consequences (technical, economic, social, environmental) of management decisions based on the analysis of all internal and external relations of the management object;
- consideration of all possible options for achieving the target results, differing in the combination of resources used, methods of their attraction and application;
- determination of technical and economic risks and uncertainty in obtaining the target results of a management decision.

Such solutions require a systematic approach, taking into account all non-linear relationships within complex systems, consideration from the standpoint of the full life cycle. In this regard, the most appropriate methodology for their adoption and subsequent implementation is systems engineering.

Systems engineering has entered engineering practice as a way to overcome the complexity of developed and maintained systems, as an interdisciplinary approach and as a tool necessary to create successful systems that can meet wants and needs of customers, users and other interested parties. The application of this approach allows us to reduce the risks and impact of system errors, to ensure interaction at the intersection of disciplines, where unforeseen difficulties most often arise.

Engineering disciplines are most closely related to a particular field of knowledge in which they specialise, and are less involved in the process of creating value. In contrast, systems engineering in the latest concepts [Systems engineering vision.., 2021] is less focused on a specific area of knowledge (mechanics, optics, chemistry, etc.) and to the greatest extent on the values and needs of stakeholders. At its core, systems engineering is interdisciplinary. To create a successful system, it is necessary to be a professional not only in at least one of the subject areas that define the system, but also to have sufficiently deep knowledge in other areas, to have the competence to communicate with specialists in various fields of science and practice, and to understand the needs of future users.

One of the founders of systems engineering - A. Sage - defined systems engineering as a management technology that is more related to technical leadership and system management, which determines the development of technologies, than to certain methods used to develop and maintain successful systems [Sage, Rouse , 2009]. At the same time, he distinguishes three levels of systems engineering. The lower level is the technology level that ensures the creation, use and maintenance of the system. The middle level is the level of methodologies that determines the direction of efforts and the coherence of the work of all project participants. The upper level is the level of system management, which ensures interaction with the external environment, the development of a strategy, and the choice of the direction of the organisation's development. Insufficient attention to the problems of this level negates all the efforts of the project team, dooming it to failure, despite the good elaboration of details and the coordinated activities of the participants.

All levels of systems engineering are interconnected and intensively exchange information. Each level has its own type of knowledge, which is also closely related. Knowledge of practices that accumulate skills and experience allows you to effectively and consistently act in standard situations and solve emerging problems in known ways. Knowing the principles that formalise problem solving allows you to cope with unexpected situations, work in conditions of uncertainty, develop new systems and practices. Knowledge of the prospects, both the directions of development of one's industry and related areas, and changes in the external environment, allows one to participate in the implementation of large projects, develop and maintain complex systems, and ensure the competitiveness of the organisation. Success requires all three types of knowledge and good organisation of the relationships between them, as well as continuous learning by doing and expanding existing knowledge.

System engineering processes involve the quantitative and qualitative formulation of goals, objectives and alternative solutions, the analysis of acceptable alternatives and the interpretation of its results from the standpoint of influencing the final result. These activities are performed iteratively as information and knowledge are accumulated, and provide solutions to problems as they arise. To perform these actions, systems engineering has an extensive arsenal of tools, which is replenished as systems become more complex and new problems are solved. Each level uses its own set of tools, but they are all integrated and coordinated with each other.

Each of the organisations that apply systems engineering methodologies adapts for itself a set of methods and tools used at the lower level (technology level). All of them have strong computer support and are closely associated with the systems

Table 6
Competences required during modernization

Competency	Required level		
	Engineer	Economist	Manager
Ability to formulate goals, prioritise, make adjustments when external conditions change	***	**	***
Ability to quickly respond to changing external conditions	**	**	***
The ability to catch signs of emerging problems and evaluate solutions before a negative effect manifests itself	***	***	***
Ability to assess the dynamics of change, select meaningful indicators, ensure correct measurement and analyse results	***	***	***
Ability to comprehensively assess the consequences of decisions made (analyse expected results from a business perspective)	***	***	***
Skills of constructive communication with external organisations, active exchange of information and reaching compromises	**	*	***
Ability to evaluate efficiency from the point of view of the entire life cycle	***	***	**
Ability to identify critical resources and ensure their efficient use	***	**	***
Possession of modern methods and tools for analysis and modeling	***	***	**
Ability to understand the needs and desires of customers and technically ensure their implementation	***	**	***

Note. Levels of development of competencies: * – initial (basic), ** – average (confidently owns), *** – highest (professional).

Table 7
Examples of training modules and interdisciplinary competencies formed in the master's program

Module	Type of formed competencies	Specific competencies as a result of training
Science-intensive technologies are the basis for the digitalisation of the industry	Engineering, economics and digital resource management	Development of an engineering project concept for a new product
Personnel and competencies for the digital economy	Soft	Professional self-development, build-up and use of creative potential. Solving complex organisational and managerial tasks based on the application of system analysis
Leadership in digital reality	Proactive Action	Development of business models and leadership strategies for businesses in the digital environment
Economy - finance - investment of innovative business	Engineering and economic	Application of analytical and financial investment tools in making proactive decisions
IT resources of innovative business	Digital resource management	Ensuring the interface of organisational systems with information technology
Startups and technology entrepreneurship	Engineering and management	Holistic vision of the system: trends - breakthrough technologies - promising markets - the intellectual potential of the organisation
Proactive management	Proactive Action	Creation of a system for early detection of new opportunities
Risks in the face of uncertainty		Formation of development concepts in conditions of uncertainty
Strategic context		Research and analysis of new markets and technologies

Table 8
Implementation of an interdisciplinary approach in training managers

Aims of professional training	Directions and methods of mastering interdisciplinarity
Management students Mastering basic knowledge. Ability to apply them in non-standard situations	• Areas of new scientific and technological achievements, industry technologies and understanding of changes in the content of management activities • Organisation of complex R&D using knowledge from different fields • Development of systemic, conceptual, strategic and cost thinking • Concept design • Business games, teamwork
Lower managers Understanding of management tasks and basic management systems. Ability to solve non-typical tasks for your level. Ability to work with people and small groups. Mastering the basics of value thinking	• Demonstration of the diversity and complexity of managerial knowledge (for engineering graduates) • Best practice training with case studies • Business games, strategic sessions, teamwork in solving engineering and management problems
Middle managers The ability to solve non-standard tasks for your level, analyse problem situations, formulate and solve problems. Development of systems thinking	• Integration of management knowledge into entire system • Training on best practices with case studies • Conceptual design of tasks for the development of their field of activity • Business games, strategic sessions, teamwork to solve innovative problems
Top managers Ability to integrate economic, industrial, environmental, political and cultural goals and solve complex problems. Identify and develop growth points, create breakthrough teams; organise large-scale transformations	• Shaping a vision for the future • Methods for generating business ideas • Behavior in extreme situations • Developing the ability to change vision, strategy and task priorities • Conceptual design of the future • Business games, strategic sessions, teamwork to solve the problems of developing and implementing a strategy

methodology, tied to the system life cycle processes and focused on priorities set at the top level.

The customer organisation needs to have employees who are able to interact effectively with designers, suppliers, as well as service organisations, so that the object being created is most consistent with the purpose, operating conditions and cost-effectiveness requirements. The technical personnel who will operate the facility must be trained during the process of developing, building and debugging the system. Other employees involved in the operation and maintenance of a new facility should not only understand its capabilities and features, but also ensure the most efficient use of assets and extend their life. At the same time, managers, economists, engineers need to master new competencies, which can practically be implemented in a team. For example, Table. 6 shows significant competencies common to all participants in the process of technological modernisation in the industry.

Local modernisation, associated with the replacement of equipment at an existing facility and bringing the infrastructure into line, also requires the use of systems engineering, although to a lesser extent. Nevertheless, most of those competencies listed in Table. 6 will be relevant in this case as well. Improvement of technology, replacement of individual units of installed equipment to extend the service life can generally be performed by traditional methods. However, even in this case, a comprehensive assessment of all the consequences, a comparison of different options for action in the context of strategic objectives and alternative technical solutions will be required. Therefore, most of the listed competencies will be required in this option, although not at such a high professional level.

It is important to emphasise that managers and engineers who are able to work in a single team and, therefore, have a common conceptual language, a holistic vision of the object of improvement, and who own the tools and means of network communications are becoming more and more in demand. In this regard, we note that in the programs for the management of engineering described above, focused on the training of innovative managers, issues related to systems engineering are given special attention. The use of systems engineering courses in the training programs for managers, economists, IT specialists is an increasingly common practice in foreign universities.

When preparing masters of management in the programs "Energy Business" and "Management of Innovations in the Digital Economy", the authors of this work have been implementing the original course "Systems Engineering for Managers" for more than five years. This course is aimed at mastering a systematic approach to solving managerial problems in the creation and development of complex systems in a dynamic environment. It is focused on the formation of systems thinking among masters, the development of system practices, solutions taking into account the interests of key stakeholders throughout the entire product life cycle. The course examines the development directions of systems engineering, providing an interdisciplinary approach to identifying and solving emerging problems that have no analogues in the past.

4. . Principles of formation of interdisciplinary competencies of managers

The formation of interdisciplinary competencies of managers is influenced by the following patterns of this process.

Managerial competence cannot be formed only in academic work within the framework of one discipline due to the multifaceted tasks of a manager. This requires training modules that include disciplines that provide individual structural elements of competence, and a project that forms its integral content.

The training module should contain educational, practical and project tasks that require the application of knowledge from all disciplines of the module, due to which interdisciplinary links are identified that ensure the integration of the studied content into the practical ability to solve specific problems.

This approach was used by the authors to develop training modules in the master's program, implemented using the original technology "Conveyor of Continuous Competence Development" [Gitelman et al., 2020c]. Each module is aimed at the formation of specific competencies corresponding to the competence model of the future industry manager (Table 7).

The goals and methods of interdisciplinary training of managers at different job levels differ from each other. So, for lower-level managers, the most important is the assimilation of the relationship between control systems and the ability to solve non-standard tasks. The priority for top managers is the formation of a comprehensive vision of the future, the development of competencies for large-scale transformations, human capital management, and the transformation of strategic priorities (Table 8). With each level of responsibility, the range of interdisciplinarity increases.

Conclusion

Management activity is becoming more complex and knowledge-intensive for many reasons, among which one of the main ones is the growth in the interdisciplinarity of new tasks, especially at the junction with engineering, which is especially noticeable in the light of the problem of a technological breakthrough. For this reason, many economic and managerial competencies well known to managers in modern practice are being transformed into engineering-economic and engineering-management competencies. Approximately the same thing happens with other competencies at the junction with other areas of knowledge, most often at the junction with information sciences when solving the problems of digitalisation of business processes. Fundamental changes in the content and methodology of professional training of managers are becoming necessary. Research and design-innovation tasks come to the fore, occupying a priority place in the content of academic disciplines and interdisciplinary projects in the modules.

Interdisciplinary competencies do not appear due to even a good command of disciplinary knowledge of all training courses. To achieve interdisciplinary learning outcomes, important implementations are necessary:

1) academic disciplines that reveal the relationship between different areas of knowledge and offer tools for their integration and practical use in project tasks;
2) research experience of joint issues and problems, showing the essence and importance of interdisciplinary connections and relationships;
3) the practice of applying interdisciplinary knowledge to solve real business problems, thanks to which they are transformed into managerial competencies.

The advanced experience of foreign and domestic management education convincingly confirms this.

It is very important that an understanding of the essence and significance of interdisciplinary issues for the successful activity of a manager is formed already at the first stages of managerial education. After all, as the career grows, the range and complexity of the interdisciplinary content in the work of a manager increases, and it becomes more and more difficult to master it at each higher level. Therefore, in the training programs for managers, especially master's programs, it is necessary not only to form interdisciplinary competencies, but also to teach the practices of their analysis, evaluation and self-development.

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