COMPLEX SYSTEMS MANAGEMENT COMPETENCY FOR TECHNOLOGY MODERNIZATION

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ABSTRACT

Industrial technology modernization requires solutions to the problems of the complex systems evolution. Entities involved in the process of modernization lack unified centralized control and act as standalone businesses, while stakeholders in the processes pursue their own, all too often conflicting interests. Having to operate amid severe external uncertainty, these standalone businesses act as isolated agents, with their make-up changing at different periods, yet the success of technology modernization depends on their coordinated action. It is critical for the success of the system evolution to have enough highly qualified personnel with expertise and competencies, engineering and economic ones in the first place, that match the complexity of the systems being managed.

The article analyzes the tasks that pop up throughout the course of modernization. The analysis is used as a basis for defining engineering and economic competencies and for substantiating their significance as a key resource of the industrial systems of the future. This assumption finds a confirmation in a summary of appropriate global trends done by the authors.

Systems engineering is used as a case of the application of the competencies as part of methodologies that were created in response to challenges associated with the growing complexity of technological and organizational systems.

The study also gives examples of the need for engineering and economic competencies arising in the course of technology modernization in the electric power industry.

Keywords: complex systems, electric power industry, engineering and economic competencies, industry, systems engineering, technology modernization.

1 INTRODUCTION

Ever growing competition in the global environment forces emerging economies to speed up technological modernization of the industrial sector. Technology modernization contributes to the shaping of the present-day economy that is based on progressive scientific and technical achievements; it is a process that combines political will, economic feasibility, and technological capability.

It is expedient to consider technology modernization from the point of view of the evolution of complex systems. Entities involved in the process are standalone businesses that act amid severe external uncertainty and all too often pursue conflicting goals. Stakeholders in the process of technology modernization have their own interests that are often in contradiction with each other. The make-up of the business ‘agents’ participating in technology modernization changes over the course of time, while the cumulative result is determined by their coordinated action. Since it is impossible to exert centralized control over the process, it is essential to ensure effective cooperation among the participants.

Competences of managerial and engineering personnel largely determine whether technology modernization will be successful. Moreover, the novelty of continuously emerging tasks, the necessity for their prompt reflection, systematization and schematization that takes into account the requirements of multiple stakeholders call for interdisciplinary competences, especially *engineering and economic competences*, bringing to the foreground their fundamental importance in achieving the strategic goals of technology modernization and pushing this problem to the level of national security.

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The authors define engineering and economic competences as a combination of systemic knowledge, expertise and skills which enable professionals to solve innovation tasks based on interdisciplinary connections between sectoral technologies, the economy and environmental safety.

It is worth noting that the term 'engineering and economic competences' does not fully reflect their modern interdisciplinary character. For example, it does not mention managerial competences which play an essential role when pre-emptive decisions are made. Nevertheless, the authors consider it possible to use this concise and widespread term for industry given the practical value of focusing first and foremost on interdisciplinary connections between the engineering (technological) contour and economic results.

Engineering and economic competences consist of:

1. *Engineering competences* that embrace life cycle processes from the creation of an object to its retirement from service: designing and making a new object, its use, maintenance, technological innovations and industrial management.
2. *Economic competences* that include planning, analysis and control of costs and results of operation in structural units, fields of work and the company as a whole; as well as methods and tools used to assess costs and forecast the results of major projects, analysis of risks and assessment of the efficiency of resources use.
3. *Managerial competencies* are required for developing a business strategy, goals and tools for achieving them; they provide support to organizational transformations and an appropriate organizational culture, to internal and external communications and human resource management (selection, motivation, professional growth and skills advancement), distribution of resources and control over their use. These competencies mean being aware of factors, conditions and restrictions that influence the chances of achieving business goals and operational results; being able to act amid uncertainty and manage risks; having skills that enable one to interact with professionals, distribute duties and bear responsibility for results.

In the course of technology modernization, the scope of competences that various professionals (engineers, economists, managers) are required to possess in order to fulfil their functions is determined by the tasks handled by each mentioned category (Fig. 1).

2 TECHNOLOGICAL PARADIGM SHIFTS AND A NEW CONTENT OF COMPETENCIES

There is no doubt that broad technology modernization in manufacturing should be based on technical means arising from the latest scientific achievements, research and development in specific sectors, and, first and foremost, in the machine building sector that produces plant and machinery. However, one should bear in mind the following important circumstances.

1. Innovation breakthroughs in baseline technologies of research-intensive industries utilizing sophisticated and costly equipment (power engineering, nuclear industry, aircraft- and shipbuilding and petrochemical production) are relatively rare. That is, in this aspect the scientific and technical progress tends to move ahead discretely. During the gaps between breakthrough innovations equipment is upgraded and adjusted to specific working conditions, the potential of economic effectiveness is fully revealed and, quite importantly, production costs are reduced.

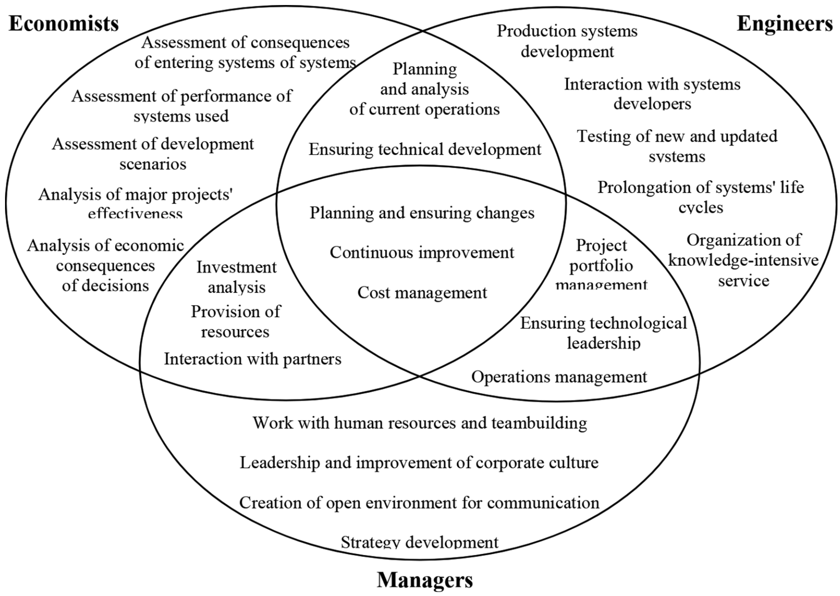

Figure 1: Tasks forming competences in the course of technology modernization.

Experience shows, however, that even such ‘partial’ modernization reveals an acute demand for engineering and economic competencies. For example, a range of unconventional projects needs to be accomplished, e.g.:

- Development of technology modernization investment projects including the feasibility study of technical and economic standards that characterize the ultimate results of modernization; development of restructuring programs in connection with production overhaul;
- Technical and economic analysis of the applicability of certain models of new machinery and equipment, various suppliers and forms of maintenance services in the specific conditions of a company;
- Comprehensive assessment of external risks (investment and technical ones) and ways of risk minimization;
- Big data analytics covering various thematic fields and operations in global innovation markets when implementing modernization programs.

2. The problem of competencies is exacerbated amid radical technological transformations that are typical today of top manufacturing countries Many countries are beginning to experience a rapid growth of the industry of the future (Industry 4.0) based on cyber-physical systems (CPS), which connect the virtual space of the internet with industrial equipment via a complex of network technologies. The production environment of such industry is rich in information technologies, measuring systems and robotic solutions. As a result, industrial architecture and traditional production change fundamentally. Nowadays, the industry of the future is only taking its first steps, but it is obvious that further on the convergence of its achievements with technology modernization will increase.

The uneven development of complex technological systems is manifested at the pre-investment stage and sometimes there emerges a problem of integration of innovations – ‘the effect of phase rejection/alienation – a war of technological batches which belong to different phases of development’ [1].

Infrastructure, including critical infrastructure, proves to be unprepared for the functioning of the new systems; for instance, the power sector turns out to be not ready for electrification of smart production facilities that have special requirements in terms of the reliability and quality of the power supply.

The system of professional education has turned out to be completely unprepared for a wave of innovations accompanying technology modernization: it has showed its inability to change the paradigm in advance and arrange anticipatory training. As a result, engineers' and managers' competences do not meet the requirements of technology modernization.

That calls for a broader vision, a comprehensive approach to cutting-edge scientific and technical achievements, emerging technological trends and new competences as well as changes in professional education.

3. Contradictions between the goals of the scientific and technical fields (science), users of equipment (operation) and interests of business as the main customer of science-driven technological innovations will definitely grow.

   Science (research, concepts, solutions, development and engineering efforts) aims to achieve, first and foremost, high-technological parameters and to add conceptually new, sometimes unique quality characteristics to equipment. The examples here are self-regulation and self-recovery based on intellectualized automation, operational and functional information value, miniaturization. *Operation* has its own requirements for new equipment, including long-term stability of technical parameters in various operating modes; serviceability; high reliability of all components; ergonomics and a steady connection of the operator with smart automatic control systems. *Business* aims to ensure a high competitive edge and an increase in the company's value thanks to the use of the system throughout its entire service life. In addition, business has to take into account environmental characteristics of innovations which directly affect the profitability of production.

The above-mentioned controversies slow down technology modernization and call for the use of the system of systems management and appropriate interdisciplinary competencies.

3 DEVELOPMENT OF METHODOLOGY OF COMPLEX SYSTEMS MANAGEMENT

As the structural and dynamic complexity of engineering systems grows [2] and technological renewal gains its speed, developers are faced with tasks that cannot be solved by means of the conventional engineering approach based on decomposition. Systems assembled from parts (subsystems) which were created separately prove to be inoperable: they cannot fulfil target functions at the required level and their operation is hampered with unexpected problems. A good illustration thereof may be the construction of a modern power generating unit: its components (turbine, boiler, pumps) were supplied by well-known international companies but after the parts were assembled into one system, the integrated automation system exhibited a lower reliability level than expected. Designing, creating and servicing such systems require a different approach.

Above all, it requires well-coordinated work of interdisciplinary teams, whose specialists join the process at different stages and fulfil different functions. Under such conditions, it is impossible to foresee the results of the decisions that are made at earlier stages and which dramatically influence the effectiveness of the development process and characteristics of the system being created. On the one hand, in this situation, it is necessary to assess options, keeping in mind the entire life cycle of the system and external environment changes which can have a significant impact on it [3]. On the other hand, it is necessary to separate the designing of the system in general from detailed work on its components and to develop the system on an iterative basis, checking and adjusting solutions as new information comes in [4].

As new technologies tend to spread quickly and compete against each other, they give rise to solutions that are still 'fresh' and have not reached their plateau of productivity yet, to go outdated. The use of the latest technical achievements provides a competitive edge but also bears the risks of developing a dependence on insufficiently developed technologies or combinations of technologies which have incompatible goals [5].

As a result of the abovementioned challenges innovation-driven economies, the USA in the first place, are experiencing an active development of new specialized methods which help revise traditional approaches to making adequate engineering and managerial decisions (systems engineering, conceptual engineering and design thinking, futures studies, horizon scanning, weak signal management, etc.). Systems engineering is the most applicable one among these methods. It is based on the interdisciplinary approach and instruments essential for the creation of complex systems (Fig. 2).

Systems engineering envisages interrelated and coordinated activities at three levels. *The lower level* - the level of technologies – provides for creation, operation and management of the system. *The medium level* –the level of methodology –determines the direction of efforts and coordination of work of all participants in the project. *The upper level* – the level of systems management –provides for interaction with the external environment, strategy development and selection of the direction in which the organization will develop.

A particular kind of awareness corresponds to each level. *The awareness of principles* which formalize problem solving helps cope with emergencies, work amid uncertainty, develop new systems and work out new practices. *The awareness of practices* which combine skills and expertise helps effectively act in standard situations with coordination of efforts. *The awareness of prospects,* that is, of the development trends in one's own and related industries as well as of changes in the external environment, helps participate in the implementation of major projects. Each level uses its own set of means, methods and tools, but they all are integrated and coordinated.

The international community of systems engineers has developed and tried out a combination of theoretical and practical recommendations on complex systems creation. An integrated combination of international standards and best practices which contains rules and regulations on systems development and their life cycle management has been built [6]. What is special about applying standards like ISO/IEC 15288 and ISO/IEC 12207 is that each sector or large corporation can work out their own regulatory documents aligned with their corpo-

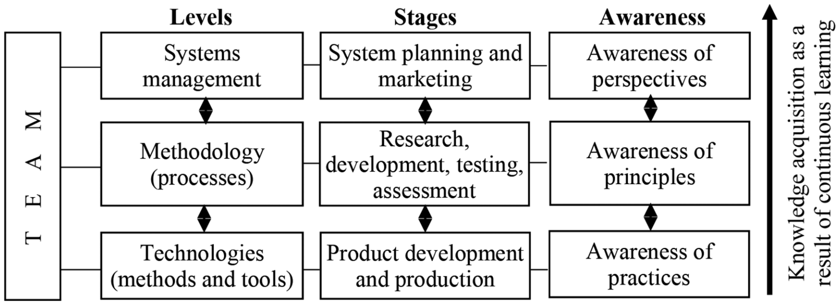

Figure 2: Conceptual framework of systems engineering. *Adapted from of Sage A* [3].

rate needs. Based on the results obtained, a system of methods and instruments to manage life cycle processes when constructing systems is determined.

At this stage of systems engineering development a number of new trends have emerged, and coordination with various managerial disciplines has come into the spotlight. One of the new fields is systems of systems engineering (SoSE) [7, 8]. Systems engineering which dealt with complex technical ('hard') systems at an early stage has shifted the focus toward the problems of the creation of 'soft' socio-technical systems [9] and company-level systems [10].

Systems engineers are in charge of developing complex technical systems. Their main competences include the following abilities [11–13]:

- to identify requirements of all parties concerned, define requirements for the system and manage requirements at all levels;
- to define the system concept, develop its architecture and design;
- to use up-to-date methods and instruments of systems development;
- to integrate components, test their compatibility, suitability and compliance with system requirements and users' demands;
- to use methods and instruments of systems analysis including modelling and simulation, analysis of reliability and technical- economic characteristics;
- improving life cycle processes, technical planning and risk management;
- to establish effective interaction with technical specialists in different fields, provide for communication and information exchange between different groups engaged in the development, creation, use and maintenance of the system;
- to ensure technical leadership, targeted system development and change management.

Systems management focuses on complex interdisciplinary processes management and involvement of a number of organizations and hundreds (sometimes thousands) of specialists in different fields of project implementation. Managers' performance largely depends on their ability to ensure effective interaction of all participants in the creation, use and maintenance of the system and all the parties, directly or indirectly, interested in the results of its operation.

4 CONTENT OF ENGINEERING AND ECONOMIC COMPETENCIES

Large-scale modernization during which new things are created on the basis of the latest technologies and are put into operation while outdated ones are taken out of service, needs systems engineering as much as ever. An organization designing a new product should fully master this methodology and have enough systems engineers for the implementation of such projects. Suppliers of equipment, software and other components also should master the systems engineering approach for the successful fulfilment of their own tasks.

The client organization should have employees who can effectively interact with designers, suppliers and service companies to ensure that the object being created will be most suitable for its purposes, operating conditions and be economically viable. Technical staff who will operate the object should receive training during the designing, creation and testing of the system. The rest of the staff to be engaged in the operation and maintenance of the new facility or product should not only understand its capabilities and features but also ensure the most effective use of assets and their longest life cycle. The new competencies must be mastered by managers, economists and engineers. This task is easier to accomplish through teamwork. Some competencies that are equally essential for all parties involved in the process of modernization are shown in Table 1.

Table 1: Competencies required for modernization.

Competencies	Required level 1		
	Engineer	Economist	Manager
Ability to set goals, prioritize, make adjustments if external conditions change	***	***	***
Ability to promptly react to changes of external conditions	**	**	***
Ability to detect signs of emerging problems and assess possible solutions before a negative effect is manifested	***	***	***
Ability to assess dynamics of changes, select relevant criteria, ensure correct measurement and analyze results	***	***	***
Ability to make a comprehensive assessment of consequences of decisions made (analyze expected results from business' point of view)	***	***	***
Practical skills of effective communication with outside organizations, active exchange of information and reaching compromise	***	**	***
Ability to assess effectiveness from the perspective of entire life cycle	***	***	**
Ability to determine critical resources and ensure their effective use	***	***	***
Ability to use up-to-date methods and instruments of analysis and modelling	***	***	**
Ability to understand clients' demands and desires and ensure their technical implementation	***	**	***

1 Levels of competence: ** – intermediate (medium), *** – upper (expert)

Local modernization involving the replacement of equipment at an operating facility and relevant adjustment of infrastructure also requires the use of systems engineering, to a lesser extent though. Nevertheless, most of the competences listed in Table 1 will be relevant as well.

Technological improvement, replacement of separate units of the installed equipment in order to extend its service life may be carried out using traditional methods. However, this situation also requires a comprehensive assessment of all consequences, comparison of various options in the context of strategic tasks and alternative technical solutions. Therefore, most of the above-mentioned competences will be relevant in this situation, too, albeit not at such a high professional level.

We suggest considering the most important aspects of technology modernization using the case of the power industry. In this industry, engineering and economic competences have a key importance as they provide for the functioning and development of an energy company and its technical, technological and economic systems as a whole for the sake of increasing reliability and security. These competences are required for substantiation and the decision-making process in virtually all spheres (logistics, finances, marketing, strategic management, etc.).

For instance, when handling the logistics of fuel supplies to a thermal power plant one should understand that boilers work on a fuel of particular quality (characteristics) that comes from specific suppliers and at a particular price; when handling financial operations and planning the company's budget one should be aware of the connection between the energy unit's efficiency and business results; energy marketing models the rational behavior of the active customer who buys relevant services from the energy system on the energy and capacity market.

Equipment in the power industry is a sophisticated engineering and technical system, in which reaching the designed parameters takes a considerable amount of time and which has a long service life and therefore requires maintenance and modernization. The latter includes the following.

1. Technical modernization of the key equipment of thermal power plants (replacement of operating energy units) using one of the following options: either by means of installing cutting-edge machinery and technology, for instance, replacing a steam-power energy unit with a combined cycle power unit, or by replacing an operating energy unit with more advanced equipment, which has enhanced steam conditions among other things. It is noteworthy that the first scenario implies that technological modernization is carried out on the power plant's premises, whereas in the second scenario it takes place in the field of power plant engineering.
2. Extension of economic life (standard service life of the equipment) by means of replacing basic units, carrying out recovery heat treatment, derating steam conditions, etc. These measures are quite important and relevant as they make it possible to delay capital-intensive modernization solutions in case of a shortage of investment resources.
3. Improvement of the system of new equipment maintenance. For instance, condition-based maintenance will require technological modernization in the process of repairs: fitting it with up-to-date diagnostic equipment, service maintenance by manufacturers, developing relevant technological and logistics infrastructure.

The above-mentioned measures of technology modernization are implemented to a certain extent, which makes it possible to ensure better efficiency. At the same time, there is a drastic shortage of specialists with engineering and economic competences. The problem becomes even more serious if we look at it from the electricity consumer's perspective in the context of scientific and technical progress at a new electrification stage which is characterized by the integration of smart grids and power-consuming systems into single self-adaptive and self-regulating manufacturing clusters. Structural and market effects are beginning to play a major role at this electrification stage: new jobs and professions are emerging and new markets and related technologies are developing. For instance, due to the appearance of high-speed rail lines and smart automobile infrastructure, in the next 5 to 7 years the transportation sector will have an explosive demand for chemists and specialists dealing with new materials, software engineers, industrial designers, urban economists and service systems designers [14, 15].

People working in manufacturing that is the main consumer of electricity (according to different estimates, the industrial sector accounts for 40%–50% of the total electricity consumption) are beginning to realize that it is companies rather than international or regional expert agencies alone who should monitor technology development in the power industry. For example, in-house analysts are assigned the duty of technology foresight which involves regular discussions with scientists, engineers, managers and economists [16]. In a number of companies, specialized interdisciplinary councils are being set up in order to look for answers to questions such as:

1. How will the company's energy system change after a particular technological innovation is introduced.

2. What are the prospects of an innovation and technical risks relating to it? (Is it possible that things will change soon and the company will have to spend a lot of money on new equipment, personnel training and infrastructure development again?) Is it compatible with other breakthrough innovations in the industry, fuel and energy complex, smart city environment? What amount of investment will be required and what effects (economic, environmental ones) are to be expected.
3. How will the introduction of new energy technologies affect the company's market stability as regards customer value and new sought-after qualities of the end product? In order to answer these and similar questions the participants should master engineering and economic competences at a level that will enable them to establish effective interdisciplinary communication. It is obvious that without a new range of engineering and economic competences such work is impossible.

In general, it can be noted that a trend for further changes in engineering and economic competences of specialists in the power industry is linked to a number of factors:

1. Energy markets' development and stronger competition;
2. Introduction of smart grids;
3. Diversification of business and development of relations between energy suppliers and consumers.

It is about the strengthening of the existing and the arrival of new forms of technical and economic ties in the supplier-consumer circuit, including the parameters of energy quality and reliability (exchange of information, mutual financial responsibility for reliability and quality, new economic methods of managing production reliability and efficiency, particularly various mechanisms of demand-side management). Economy-wise, the spotlight is being shifted from production to a service- and customer-oriented approach. All these will add more aspects to the process of cost-benefit planning.

With energy demand-side management gaining potential, engineering and economic competences will include the following competences (Table 2).

An insufficient level of engineering-economic competences required to make the decisions mentioned above creates barriers to implementing demand-side management programs. Given the fact that such programs require the consideration of development prospects, the absence of an efficient demand management mechanism is becoming a significant obstacle to technology modernization. We could provide more examples but a general conclusion is that nowadays the development of engineering and economic competences of professionals and top managers is a crucial factor in technology modernization.

5 DEVELOPMENT OF ENGINEERING AND ECONOMIC COMPETENCES AS A GLOBAL TREND

An analysis of job requirements and educational programs offered by many universities shows a growing interest in professionals with a wide range of competencies. The trend is reflected in the works published by leading research centers. For example, the Institute for the Future for the University of Phoenix Research Institute (USA) has designed a map of skills and competences [17] that will be needed by managers in various fields of the new industry (Fig. 3).

A comprehensive vision of organizational processes and business development potential is an essential part of competences for managers of the future industry. It grows out of having a clear understanding of global context; understanding how technological modernization

Table 2: Engineering and economic competences for demand-side management programmes.

Solution type	Solutions	
	For energy company	For customer
Engineering	Assessment of opportunities for growth, flexibility and capacity of generation equipment; Adjustment of the power unit schedule in t(he grid and the mix of generating plants for instance, deciding against putting costly peak hour capacity into service, or increasing installed capacity utilization factor of base load power plants); Cutting volumes of backup grid capacity; Introduction of remote load control systems and IT technologies in the 'supplier-consumer' contour.	Switching units to 'controlled load consumer' mode; Increasing unit capacity in off-peak hours; Amending schedule of equipment maintenance; Night shifts arrangement.
Economic	Planning and assessment of energy and capacity savings after implementation of demand-side management programs; Cutting operating costs and capital investment in new capacity, peak hour facilities in the first place; Budget and efficiency of the program; Economic motivation mechanism for customers.	All costs on changes in electricity consumption regimes; Result (effect) and effectiveness given privileges and preferences relating to lower payments for electricity and capacity provided by energy company.
Managerial	Design of demand-side management programs; Coordination of schedule of program' implementation with authorities, energy service companies, suppliers of equipment; Development of incentives for participants in the programs.	Institutionalization of participation in demand-side management programs (creating internal regulatory systems, rules, training of people in charge, adjustment of business processes, etc.)

processes affect business model; ability to use methods of creating flexible organizational structures; strategic thinking [18, 19].

A liking for visualization of strategies, project solutions or new products is what distinguishes managers and engineers of the industry of the future: it is believed that innovations cannot be created if the person in charge has only mastered a limited number of visual tools [20]. The mindset of specialists is therefore becoming increasingly 'design-tuned' and

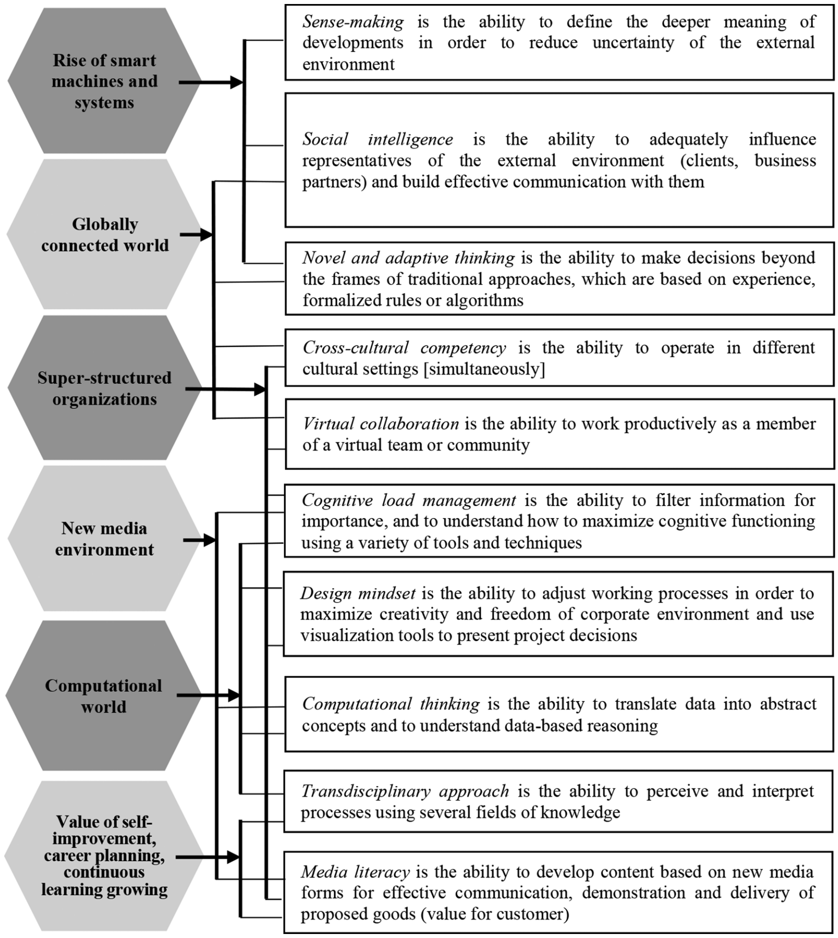

Figure 3: Map of competences for future industry. *Adapted from* [17, 20–22].

'computational' at the same time. That shows in many aspects of their professional activity: from new approaches to workplace and process organization where openness and creative freedom are deemed to be the key attributes of corporate culture, to being handy with IT systems and numerous software solutions (including such classics as Microsoft Office to specialty software for making effective presentations, preference management, business analytics etc.).

The case of Airbus [23] is a good illustration of an interdisciplinary approach to nurturing engineering and economic competencies. The competency profile of an engineer consists of four blocks: 1) generic engineering disciplines; 2) systems engineering and technical management; 3) innovation management, leadership and soft skills; 4) transversal business cases.

In general, one can infer that engineering and economic competences are a key resource of the industrial system of the future.

6 CONCLUSION

An avalanche of new technologies and stronger competition call for technology modernization which is impossible without new engineering and economic competences. These competences should be in line with contemporary methods of complex systems development management. The methods include such important components as the interdisciplinary approach, systems thinking, adaptability, iteration of processes, assessment of decisions being made from the perspective of system life cycle as well as active exchange of information and interaction of participants working at different stages of this cycle.

Finding a solution to the problem of building engineering and economic competences will make it possible to bring down the complexity of technology modernization to a level where it is possible to control the process, identify and mitigate risks.

The task of building engineering and economic competences can be accomplished through targeted research that is focused on foreseeing scientific and technological development trends and creating a vision of the future, summarizing the best complex system management practices and integrating the results into new-generation educational programs.

The authors' experience of consulting in the energy sector, directing interdisciplinary bachelor and master degree programs in energy business and innovation and transformation management at Ural Federal University, training of innovation-minded breakthrough teams for technology modernization at the university and major corporations enables them to state confidently that engineering and economic competencies get filled with substance through close cooperation between partners in education, science and business, that is, through smart partnership established for the sake of implementing the strategy of leadership by each party involved [24, 25].

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