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Systems literacy – A new perspective for innovation managers and engineers

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Abstract

The article presents the results of a study that confirms the high relevance of developing a new critical competence among specialists involved in technological modernisation and import substitution projects – systems literacy, which requires a holistic vision of the interdisciplinary relationships of complex systems. The authors demonstrate that systems literacy is based on systems thinking and systems engineering methodologies, which are particularly relevant to the development of sociotechnical systems that include components of different nature, and their operation throughout their life cycle. An analysis of the differences between engineering and management views of complexity has been carried out, justifying the need to train innovative teams that bring together specialists from different disciplines. The requirements for a new generation of educational products providing advanced training in engineering and economic skills necessary for the development of integrated solutions to complex problems are formulated, and the relevant experience of the Department of Energy and Industrial The management systems of the Ural Federal University, tested in the training of high-tech managers, are presented. The specificity of the application of systems literacy is illustrated by the example of the energy transition problem, which directly determines the achievement of technological sovereignty and involves deep transformations in various industries and market entities.

Keywords: systems literacy, systems approach, systems engineering, interdisciplinarity, modelling, life cycle, innovation.

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系统思维是创新经理和工程师的新视角

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简介

文章中提供了研究结果，证实了在参与技术现代化和替代进口项目的专家中，形成一种新的关键能力——系统思维的高度重要性。这种能力意味着能够全面理解复杂系统之间跨学科的相互关系。研究表明，系统思维的基础是系统工程思维和方法的掌握，这在开发包含不同性质组件的社会技术系统，并在其整个生命周期内进行操作时尤为重要。分析了工程师和管理者在复杂性问题上的不同观点，从而论证了跨学科专家组成的创新团队的需求。 新一代教育产品的要求已经明确，这些产品实现了对工程经济能力的超前培训，这种能力对于解决复杂问题并采取综合性解决方案至关重要。文章提及了乌拉尔联邦大学能源与工业企业管理系在培养高科技业务领导者时所获得的相关经验。

系统思维的应用特点可以通过能源转型问题来展示，这直接影响到技术主权的实现，并预示在不同行业和市场主体中进行深刻变革。

关键词：系统方法，系统工程，跨学科，建模，生命周期，创新。

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Introduction

The rapid development of technology, global megatrends, the spread of digital ecosystems, the diversity of heterogeneous data, and the expansion of artificial intelligence usage – all contribute to a significant increase in the complexity of systems. The creation and management of these systems throughout their lifecycle require managers and engineers to develop a deeper understanding of their nature and the dynamics of the context in which they evolve. This necessitates a systemic perception of reality[1]. Systems literacy combines conceptual knowledge (the properties and behaviour of complex objects, processes, and phenomena) with analytical and cognitive skills (viewing problems in a broad context, across multiple levels of perspective, tracking complex interconnections, analysing endogenous and exogenous factors, recognising patterns, and predicting changes in system behaviour over time to prepare proactive decision options) [Sweeney, 2018].

The need for systems literacy is driven by the following reasons:

1. Changes in nature and society, under the influence of global trends, technological development, and increased interconnections and interdependencies between individuals, market, and governmental structures, demand new approaches to assessing situations, making decisions, and organising daily activities.

2. The traditional analytical approach, based on linear cause-and-effect relationships, is no longer applicable in these conditions (it leads to unforeseen consequences and generates new problems).

3. The systemic nature of the real world has become a defining factor – it can no longer be ignored. Global crises, climate change, accelerating changes in communication development, supply chains, and the creation of platform models and ecosystems in business can only be viewed from the perspective of a systems approach.

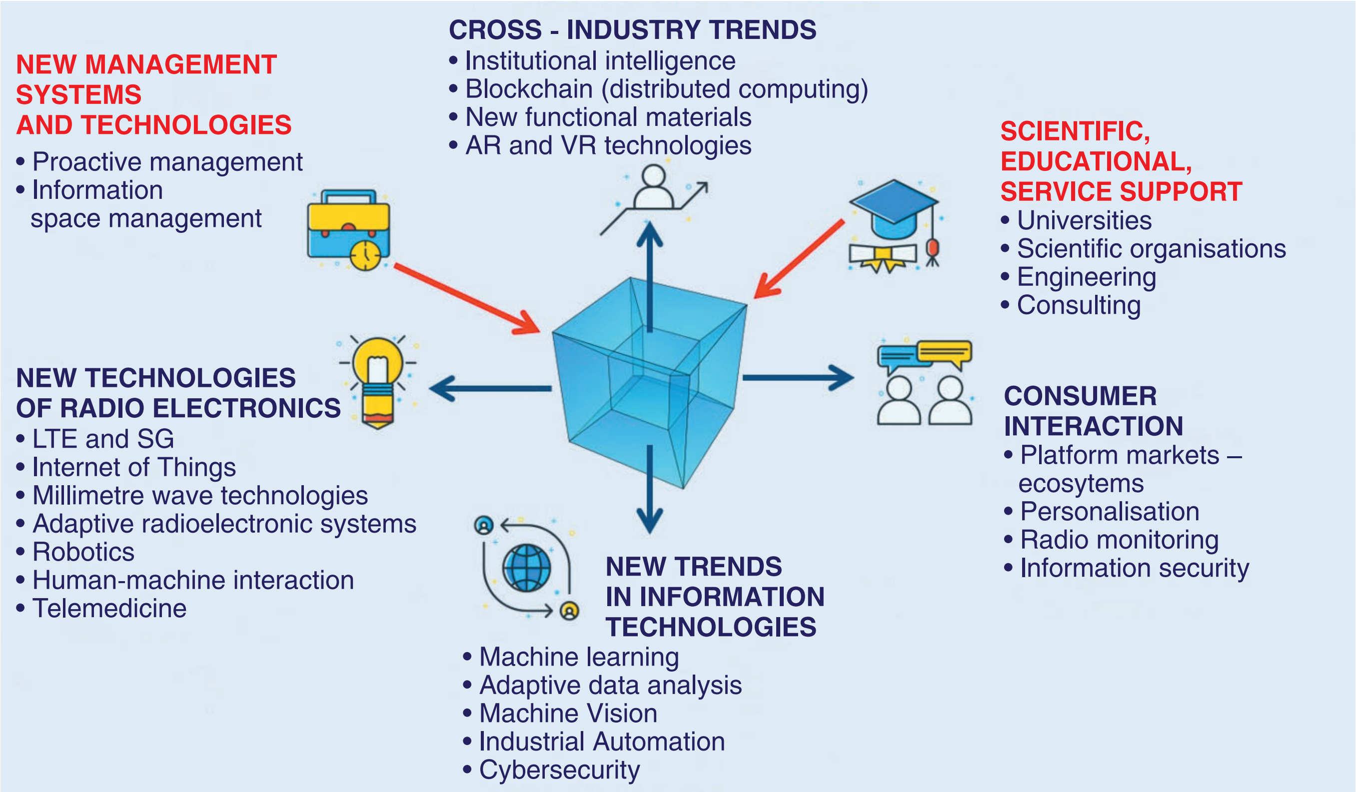
4. New ways of thinking, acting, and interacting require a comprehensive understanding of the structure and behaviour of systems from researchers, designers, managers, and specialists who prepare or make decisions.

A manager's ability to explain in a language understandable to stakeholders the system in which work is being performed, its key features, and what to expect from the system during its evolution also depends on their systems literacy [Dubberly, 2014][2]. Thus, systems literacy becomes the key to making complex engineering, financial, and organisational decisions when creating and developing systems, using a specialised professional language.

[1] Systems engineering vision 2035. Engineering solutions for a better world (2022). The International Council on Systems Engineering (INCOSE). https://www.incose.org/about-systems-engineering/se-vision-2035.

[2] See also: Sustainability studies: A systems literacy approach. (2023). https://courses.lumenlearning.com/suny-sustainability-a-comprehensive-foundation/chapter/sustainability-studies-a-systems-literacy-approach/.

Fig. 1. An example of a contextual analysis of the radio electronics and information technology industry



The foundational level of systemic literacy begins with the ability to represent a management object as a system. This involves understanding the interconnections within the system, the structure of its components, the characteristics of the system's behaviour in an external environment, and the functions it must perform throughout its life cycle. At this level, it is crucial to be able to clearly describe the system's context – the set of factors and circumstances surrounding the system that influence its condition and development.

The system context describes all external elements interacting across the boundary of the specific system of interest and provides sufficient insight into the elements within its boundaries. To fully understand the context, it is also necessary to identify the characteristics of the environment in which the system operates – the so-called systemic environment. Viewing systems in context allows us to focus on the system itself while maintaining a broader systemic perspective. As D. Martin [Martin, 2004] notes, it is important to account for the interdisciplinary influence of other systems, which to varying degrees determine the functioning and development potential of the system of interest throughout its life cycle. Additionally, it should be understood that the dynamics of the context largely depend on stakeholders, who often have differing, sometimes conflicting, views on the goals of creating systems and their interests in using them[3].

1. The Essence of the Systems Approach

The systems approach views an object (phenomenon, process) as a holon – an entity that is, in itself, a whole system, yet at the same time, part of another system, interacting with a mosaic of other holons within its broader environment, whilst also being composed of interacting parts [Koestler, 1967; Hybertson, 2009]. This means that an important skill in the systems approach is identifying 'natural holons' in problem situations and decision-making processes, as well as distributing their responsibilities for specific functions. Therefore, the systems approach defines problems, solutions, and the decision-making process itself according to the following requirements:

– Consideration of the problem as a whole, taking into account the boundaries of the problems and the interconnections of systems;
– Development of solutions that reduce organised complexity;
– Analysis of the context of the system, which generates potential problems and possible solutions (see Fig. 1).

The systems approach involves a comprehensive system perspective that encompasses the broader system context, including the engineering and operational environment, stakeholders, and the entire life cycle. A set of guiding principles has been proposed for implementing the systems approach [Hitchins, 2009].

[3] Systems literacy (2021). https://systemssciencesliteracy.org.

1. Systematic view – Any system of interest (SoI) must be considered within a broader system context.

2. Synthesis – Systems engineering should integrate all parts and develop solutions for the system as a whole.

3. Holism – When making decisions for individual elements, the impact on the entire system must always be considered.

4. Analogy with Organisms – The system should always be viewed as a living organism, changing its behaviour in response to environmental changes.

5. Adaptive Optimisation – Solve problems as they arise.

6. Progressive Entropy Reduction – At early stages of the life cycle, plan all necessary actions for maintenance, support, and system updates.

7. Adaptive Alignment – Design the system's life cycle based on the needs of critical-to-success stakeholders.

A significant application area for the systems approach is the practical use of systems engineering principles when creating and developing complex systems [Sillitto, 2010]. These principles form the foundation for guidelines on applying systems engineering processes. Depending on the purpose, application domain, and level of familiarity with the problem area, such guidelines vary widely – from heuristics (generalising practical experience) to models (developed based on theoretical work). They all support targeted judgements or actions in context, though they may differ significantly in scope, authority, and available capabilities. As experience accumulates, their applicability broadens. Systems engineering principles have diverse origins, being grounded both in practice and theory [Rousseau et al., 2022], and existing systems engineering standards and guidelines include many elements of the systems approach. Examples of principles proposed by the International Council on Systems Engineering (INCOSE)[4] include the following.

1.The application of systems engineering depends on stakeholder needs, the space and outcomes of system decisions, and changes in context throughout the system's life cycle. Consideration is given to budget, schedule, technical requirements, other expectations, and constraints.

2. Systems engineering forms a comprehensive view of the system, its elements, interactions between them, and various factors (political, economic, social, technological, environmental, legal).

3. A real system can only be described by an ideal representation, i.e., an ideal model.

4. Systems engineering decisions are made under conditions of uncertainty, taking risk into account.

5. Complex systems are developed by organised structures that are appropriate in complexity.

2. Systems literacy is developed through systems engineering methodologies

Socio-technical systems are the primary objects of design and support in systems engineering [Checkland, 1978]. These systems are inherently created for a specific purpose and require lifecycle maintenance.

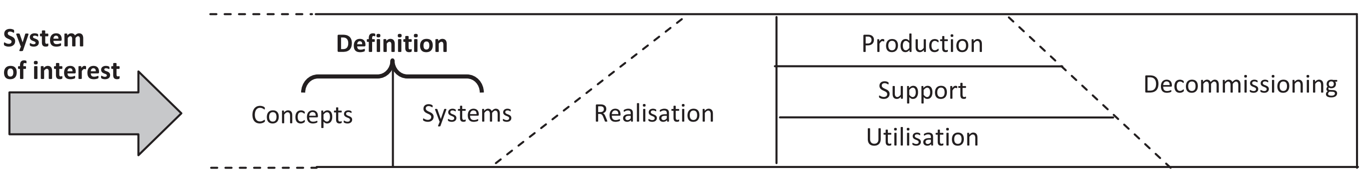
In systems engineering, the concept of the context of a designed system is used to define the system the lifecycle of which needs to be supported (SoI), as well as to identify and align key relationships between it and the systems with which it interacts directly or indirectly. The selection of the SoI boundary for specific activities depends on what can be changed and what must remain unchanged.

In the processes of design and participant interaction, it is useful to shift the boundaries: to view the system of interest narrowly, its overarching system broadly, and the immediate and broader environment as well. This way of presenting the object helps to find the most appropriate solutions in complex situations. It is also helpful to consider differences in the understanding of the system's goals and scope of use by various groups of stakeholders.

For systems engineering, overcoming complexity is of paramount importance, and several categories of complexity are distinguished. Structural complexity is determined by the number of heterogeneous elements and their interrelationships. Dynamic complexity is revealed by changes in the behaviour of the system as it performs its tasks in interaction with the external environment. Socio-political complexity is inherent in systems involving people, who add additional elements of complexity to the system's behaviour. Different types of complexity are interconnected and require attention when designing and operating systems.

Subjectively, complexity is measured by how easily an observer can understand the system or predict what will

Fig. 2. Basic model of the system life cycle



Source: adapted by the authors from: Guide to the systems engineering body of knowledge. http://sebokwiki.org/wiki/Guide_to_the_Systems_Engineering_Body_of_Knowledge_ (SEBoK).

[4] Systems engineering vision 2035… https://www.incose.org/about-systems-engineering/se-vision-2035.

happen to it in the future. Thus, it depends on the personal qualities of the observer (knowledge, comprehension).

Objectively, complexity is an attribute of complex systems, measurable within a range of values from order to complete disorder. It is defined as the degree to which it is impossible to predict the future state of the system based on knowledge of its current state and history. A range of characteristics of system elements and their interconnections is used to assess objective complexity: independence, interdependence, heterogeneity, and adaptability.

Systems engineering has accumulated extensive experience in applying the systems approach to identify and understand complex problems and opportunities, to synthesise alternative solutions, to analyse and choose the best one, and to apply the chosen solution, as well as the associated actions for deploying, using, and supporting the designed systems.

One of the fundamental principles of systems engineering is the focus on designing and supporting systems from a full lifecycle perspective. Systems engineering ensures a comprehensive study of the designed system at early stages, active engagement of all stakeholders, modification of system requirements as new information is obtained, interdisciplinary communications, and modelling of system behaviour throughout its lifecycle. This results in reduced risks and the ability to detect defects at early stages of the project. The overall lifecycle costs are significantly reduced. Projects are completed on schedule, as the time required to correct design errors is minimised. For the same reason, the risk of exceeding the project budget is reduced, and the quality of design and operational performance of the system is improved. This effect is most evident in systems characterised by rapid scalability, dynamism, interdependence, interaction with people, and the use of new and potentially hazardous technologies.

A lifecycle model identifies the key stages that a system goes through from the beginning to the end of its life (see fig. 2). Lifecycle models are mainly applied during the development stage and are closely linked to project management, planning, and decision-making.

The principal lifecycle model describes a set of lifecycle stages and their interconnections. For each stage to be successfully completed, specific technical and managerial actions are required. The set of such actions, associated with a particular stage of the lifecycle, is defined as a separate lifecycle process. The international standard defining lifecycle processes for systems, ISO/IEC/IEEE 15288:2015, includes managerial processes alongside technical ones. These include project processes, agreement processes, and organisational project-enabling processes.

The branch of systems engineering that supports the development of adaptive systems (Resilience Engineering) employs methods that prevent disruptions through proactive actions and enhance the system's survivability (restoring functionality after a failure). The characteristics of systems with resilience and the principles of their design are presented in the works of [Madni, Jackson, 2009; Jackson, 2016].

Resilience is the ability of a system to cope with adverse conditions and disruptive factors while maintaining critical functions at an acceptable level. A resilient system can withstand both predicted events and unexpected, unpredictable external changes. Resilience is achieved through built-in reserves during system creation and through self-recovery capabilities integrated into the design.

Here are examples of solutions from the energy sector aimed at increasing the resilience of energy systems:

– Complementing renewable energy sources (RES), which depend on natural conditions (temperature, wind), with mobile operational reserves (gas-turbine or combined cycle power plants);
– Implementing flexible power plants in addition to large nuclear power plants (adapting the generation structure to the load schedule);
– Developing small-scale energy solutions to regulate the balance of supply and demand. In this case, these active elements ensure reliability and meet the growing demand.

Resilience implies that a system possesses properties such as capacity, flexibility, tolerance, and cohesion [Madni, Jackson, 2009]. Capacity refers to the system's ability to survive under adverse conditions, flexibility denotes its ability to adapt when threats arise, tolerance is the system's capacity to avoid a sharp decline in functionality, and cohesion is the ability of the system's components to unite (to act as a whole) in the face of threats.

Agility is the ability of a system to successfully evolve in a constantly changing environment characterised by uncertainty and unpredictability. Agile systems possess both reactive and proactive capabilities. Generally, agility is ensured by introducing additional active elements that ensure readiness to respond, no matter what happens. For instance, in the energy sector, agility means complementing renewable energy sources with an operational reserve; this reserve increases the flexibility of the energy system, helping it adapt to the development of renewable energy.

To create agile systems and maintain their operation, it is necessary to understand the characteristics of the external environment, the nature of possible changes, and the required responses. Based on this understanding, the architecture of the agile system is developed and enhanced. The CURVE method is used for analysing external environmental factors, which structures the problem space based on key characteristics: Capriciousness, Uncertainty, Risk, Variability, and Evolution.

Based on the analysis of the problem space, the requirements for responding to changes, which the agile system may face in its operations, are formulated. For this purpose, a special tool – response situation analysis (RSA) – is used. The response requirements identified through the analysis determine the architecture of the agile system during the design process or serve as the basis for making changes to its architecture during operation.

Today, systemic solutions are in demand in various fields: for the creation of cyber-physical, service, and multi-component systems. Moreover, interest in systems engineering is growing not only in large-scale projects but also across a wide range of systems design of different complexities and sizes, as well as in the development of socio-technical systems. Furthermore, systems engineering is increasingly becoming a mandatory condition for implementing digital business transformations [Bone et al., 2019; Verhoef et al., 2021][5]. Its inherent transdisciplinary approach – involving the application of universal methods and categories from broader sciences to study specific subject areas of a particular discipline – creates conditions for generating new ideas and solving complex problems, reducing the number of errors, increasing flexibility, and strengthening user trust. Overall, the transdisciplinary approach is a way of expanding one's worldview (scientific cognition), enabling a new level of generalisation and comprehension, resulting in new insights and perspectives on current problems [Professionals in Competition, 2021].

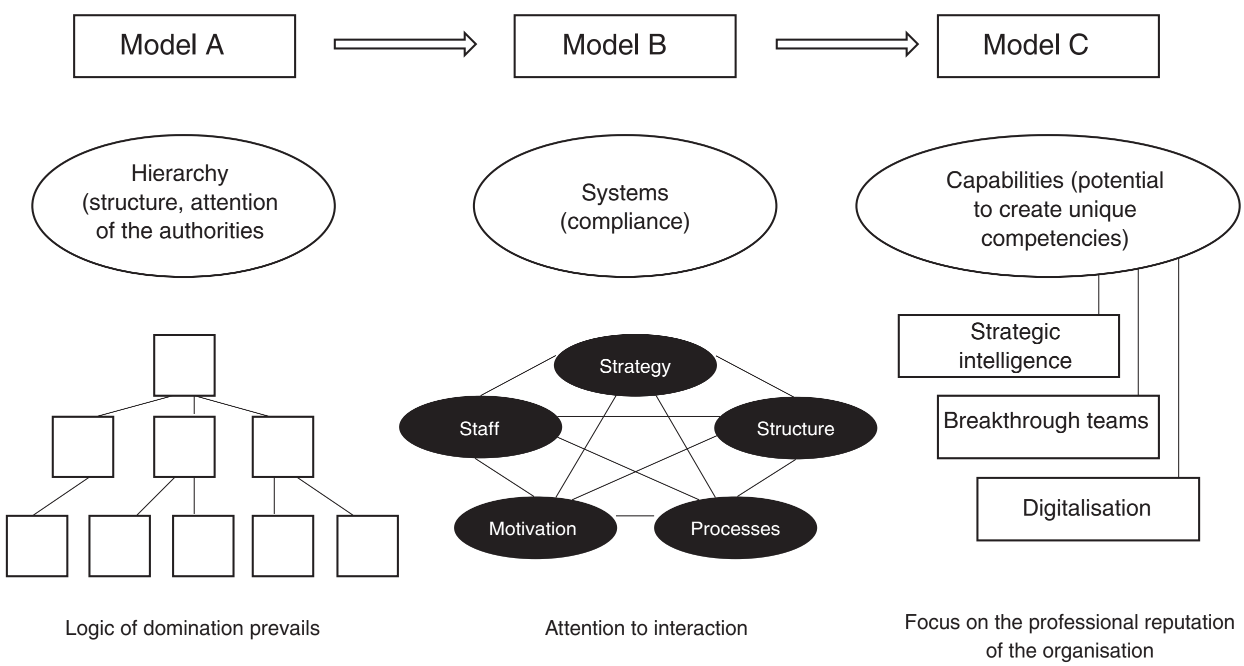
3. Engineering Perspective on Complexity

When creating and developing systems, engineers focus their efforts on overcoming objective complexity, which increases as technology advances and the field of systems engineering expands.

In the early stages of systems engineering, the main challenges were related to ensuring the coordinated operation of the system's diverse technical components and coordinating their developers. Corresponding engineering design methods were created to overcome these difficulties. These methods enable the development of complex technical systems and their maintenance throughout their lifecycle. Examples of such systems include drilling platforms, nuclear power stations, aeroplanes, and space stations. Even systems where complexity is caused by the disordered interaction of many similar elements (such as computer networks or power grids) can be modelled and regulated using statistical methods [Sheard et al., 2015].

The shift to working with higher-level complex systems has largely redirected engineers' efforts towards organised complexity [Weaver, 1948]. Organised complexity can be found in systems with many interconnected and diverse elements that exhibit certain emergent properties and phenomena, often seen in economic, political, or social systems. Such systems cannot be easily described using traditional analysis methods, nor can they be fully addressed with standard solutions or intervention methods. Therefore, the properties and functionality of such systems must be anticipated at the initial design stage (in architectural decisions), and then, by observing the system's behaviour throughout its lifecycle, necessary adjustments can be made to its structure, and their impact on the system's behaviour can be monitored.

Fig. 3. Types of organisational models and emphasis in their description



Source: [Ulrich, Jung, 2022].

[5] See also: Program managers guide to digital and agile systems engineering process transformation (2022). https://sercproddata.s3.us-east-2.amazonaws.com/technical_reports/reports/1666113204.SERC_A013_WRT-1051_Final%20Technical%20Report_V3.pdf.

Practical demands have sparked a wide range of applied research in the area of identifying and assessing system complexity. The results of these studies help in choosing the right approach to analysing, designing, and developing engineering systems. System complexity varies widely, from order to complete disorder; however, 'the real complexity of designed systems lies somewhere in the middle: they have more flexibility and variation than full order, and more stability than complete disorder' [Sheard, Mostashari, 2009].

Particular attention in the engineering view of complexity is given to the human factor. As systems scale up and socio-technical systems develop, the importance of research into human integration within systems increases manifold. When designing models of systems requiring coordinated interaction between humans and technology (e.g., flight control systems), the behaviour of people as system components, which contributes to the overall system complexity, is considered [Axelrod, Cohen, 1999]. Rational or irrational human behaviour in specific situations is a crucial factor in relation to complexity [Kline, 1995]. Some of this complexity can be reduced through education, training, and familiarisation with the system. However, certain factors are unavoidable and must be managed as part of the problem or solution. When designing socio-technical systems, this type of complexity requires separate consideration throughout the system's lifecycle [Checkland, 1999].

Thus, engineers predominantly focus on rigid systems (production complexes, equipment, machinery, units, and the information and communication networks that connect them). The primary goal for engineers is to achieve an optimal level of complexity in such systems to fulfil their functionality, ensure operational reliability for users, maintain relative ease of technical servicing, and guarantee functionality throughout the system's lifecycle.

4. Manager's Perspective: Handling Specific Models

Unlike engineers, managers deal with both hard and soft systems [Checkland, 1999]. This is due to the fact that managers work with a wider range of systems, and they must consider the interests of various stakeholders, focus on personnel motivation and training, and foster communication and collaboration. The priority for managers is business effectiveness, which leads to a specific set of criteria for evaluating systems and the processes occurring within them (see Figure 3).

In this context, the main task for managers is to reduce the subjective complexity of the systems around them, as this is directly linked to increasing the predictability of system behaviour, and, consequently, to improving control. This, in turn, allows for more accurate decision-making regarding system development, resource planning, the formation of business projects, and the creation of teams to implement them.

The problem is that the numerous objectives and outcomes of the systems for which managers are responsible often conflict with one another, are quite uncertain, and are dynamic in nature. The structure of the systems and the interests of their stakeholders, as a system-forming factor, are among the primary considerations that require attention in managerial modelling.

The ability to create models is one of the essential manifestations of systemic literacy in practice [Dubberly, 2014]. Various forms of graphical visualisation can be employed, such as feedback loops, value stream diagrams, goal and action trees, and process maps.

A model is a simplified representation of a system at a given moment in time or space, intended to facilitate understanding of the real system. As an abstraction of the system, it provides insight into one or more of its aspects: functions, structure, properties, performance, behaviour, and cost. The use of modelling and simulation at the early stages of designing complex systems allows for the documentation of functions and requirements for the system, estimation of the costs associated with its creation, identification of necessary trade-offs, and the organisation of continuous monitoring of the system's performance to enhance productivity, reduce risks, and manage costs.

Modelling and analysis can complement testing and evaluation, which occur at later stages of the life cycle. Advanced modelling, such as flight simulators and control centre simulations, can be a cost-effective method for training personnel alongside instruction on operational systems. Modelling helps to make concepts concrete and formal, enhances quality, productivity, documentation, and innovation, and reduces costs and risks associated with system development.

Modelling occurs at many levels: component, subsystem, system, and system of systems – throughout the entire life cycle of the system. Different types of models may be required to represent systems for supporting analysis, specification, design, and verification of system performance.

Fig. 4. Integrated view of the company

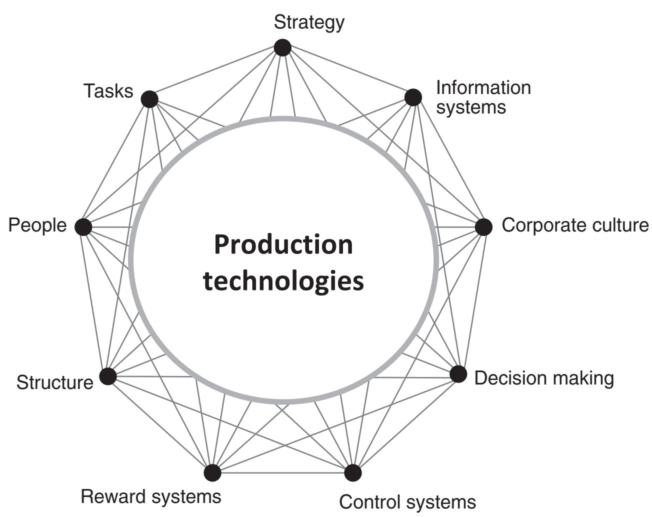
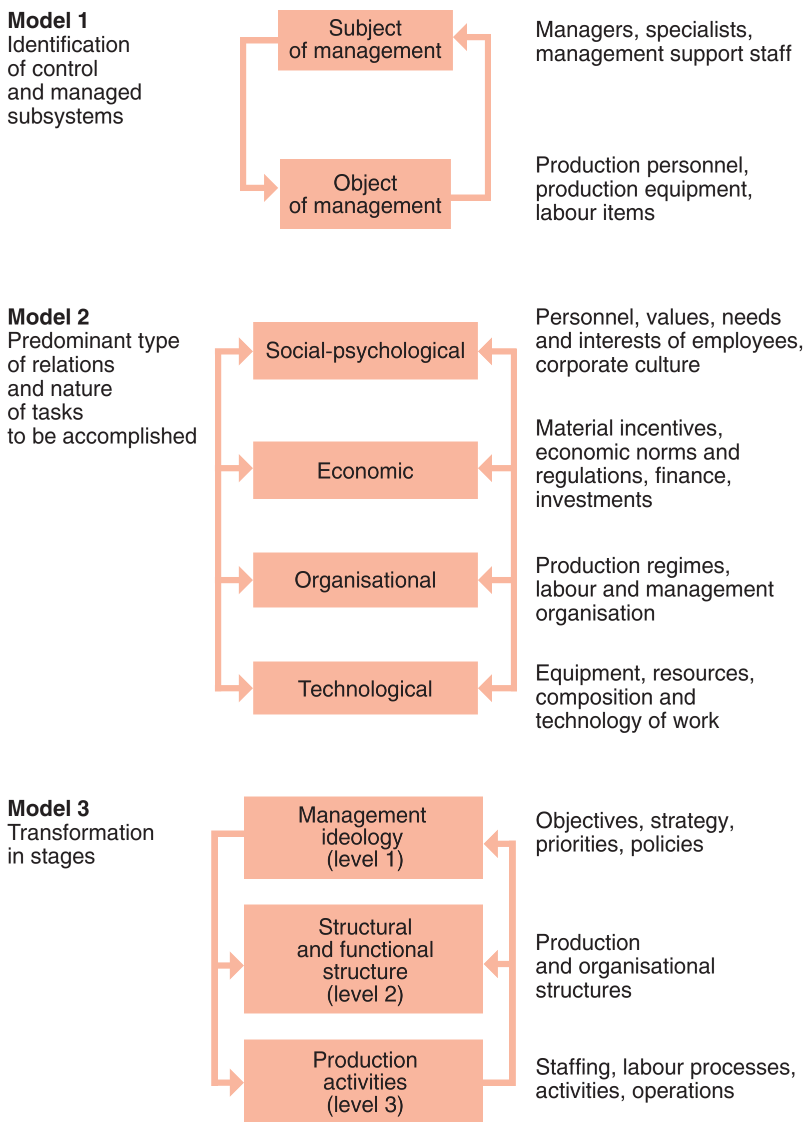


Fig. 5. Complex of business models



Modelling enables the resolution of developmental tasks: it helps to form a holistic view of activities (see Fig. 4), represent them as a structure of interconnected objects and processes, and identify the nuances of interaction with partners and customers. Therefore, for CEOs, top managers, project leaders, and innovation managers, proficiency in modelling techniques is one of the core professional competencies.

One of the most important tasks for managers, addressed through models, is the conceptual representation of business (see Fig. 5). It is this multi-faceted model representation that, by providing a more comprehensive description of the object of interest while considering the goal of accomplishing a specific task, allows for:

– working with each model and the elements (subsystems) within it using their inherent conceptual language;
– examining different aspects in the models from the perspective of interdependent requirements and proportional development of the highlighted levels, strategies, and subsystems;
– organising the staged process of change [Gitelman, 2011].

Transforming real production and management systems (see Fig. 6) is an interdisciplinary task that utilises laws, patterns, categories, and concepts from various sciences (engineering, economics, psychology, law, organisational theory, management, and others). Each of these sciences has its own theoretical foundation and conceptual apparatus. As a result, a wide variety of conceptual models and requirements are formed, which can be very challenging to reconcile in practice.

Fig. 6. Systematic approach to transformation

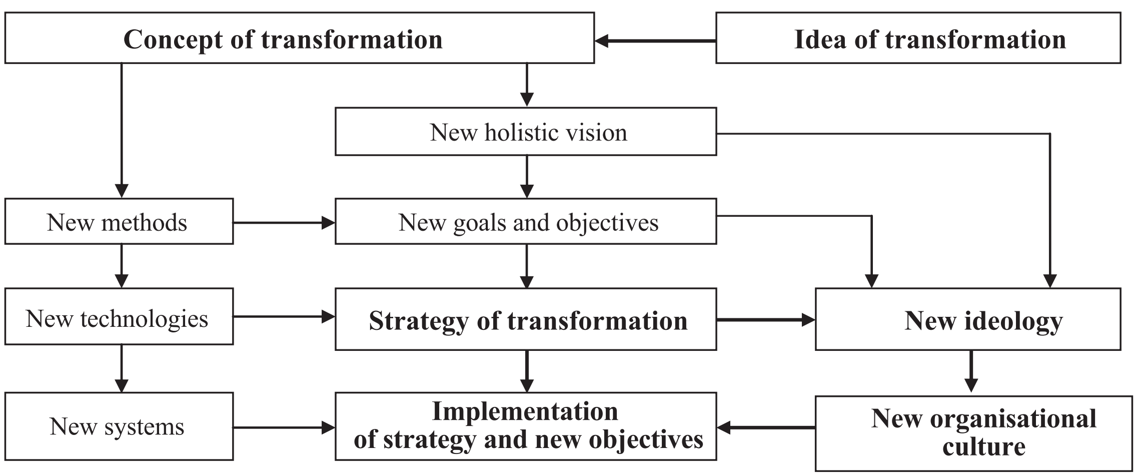


Table 1
Structure of technical and economic competences of managers

Competency clusters	Examples of competencies
Technical and economic	Economic evaluation of engineering solutions Comprehensive analytics Investment assessment in engineering innovations Cost determination and forecasting results of large projects Risk and resource efficiency assessment
Technical and managerial	Creation of early warning systems for threats and opportunities Designing the future of the company Development of leadership strategies Organisation of technological modernisation processes Managing project portfolios Organisation of proactive learning

5. A Critically Important Topic of Systems Literacy – Interdisciplinarity

By interdisciplinarity, the authors mean the synthesis of knowledge from various fields of science and practice and the identification of new interconnections between them, enabling the generation of qualitatively new solutions to complex problems. Understanding interdisciplinarity is particularly essential for managers in sectors that comprise highly complex engineering and technical systems, such as energy, telecommunications, nuclear and oil and gas industries, transport, and the aerospace sector. In these sectors, technology in the broadest sense – from targeted scientific research and engineering development to the implementation of innovations that require specific investments and corresponding financial outcomes – becomes the focal point for various kinds of connections [Gitelman et al., 2022]. Therefore, knowledge of the engineering fundamentals of production and scientific and technological trends, along with their impact on production economics, is a prerequisite for a manager to successfully perform their functions.

This thesis is well illustrated by the extremely relevant issue of the energy transition (hereafter referred to as ET) – the transformation of energy, related infrastructures, and electricity-consuming systems into a carbon-neutral model, realised through structural and technological changes that yield ecological, economic, and technological results [Balashov, 2023][6]. The implementation of the ET is an immensely complex, multifaceted, and ambiguous task, closely intertwining various interests – political, economic, ecological, scientific-technical, engineering, and social. It is evident that this is a complex systemic problem with a time horizon of at least 20–30 years, which is sufficient for realistic foresight and the consideration of breakthrough technologies in the areas of production, transmission, distribution, and, crucially, end-use of all types of energy resources [Gitelman et al., 2023b]. Consequently, the problem includes the potential for phased updating of decisions made at developmental crossroads, taking into account timely risk assessment and investment evaluation.

Interdisciplinary solutions taken during the development of ET projects require a systemic approach, accounting for all non-linear dependencies within complex systems and examining them from the perspective of their entire life cycle. For example, the specifics of employing a systemic approach to the development of the ET concept are as follows:

1) Consideration of energy production in unity and interconnection with electricity consumption through electrification and energy-saving processes.
2) Taking into account regional conditions and factors when forming the target structure of the energy system.
3) Developing the structure and operational regime of the energy system based on a multi-criteria approach that considers economic, ecological, and technical criteria and constraints.
4) A broad diversification of applied methods and organisational forms of electricity production and consumption, which complement one another, taking into account their advantages and problematic features.
5) Analysis of all consequences of using renewable energy sources, including the stages of installation production, operation, and disposal.

The most suitable methodology for making corresponding integrated decisions and their subsequent implementation is systems engineering. At the instrumental

[6] See also: Global energy transformation. A roadmap to 2050 (2018). The International Renewable Energy Agency (IRENA). https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Apr/IRENA_Report_GET_2018.pdf; Theme report on energy transition. Towards the achievement of SDG 7 and net-zero emissions (2021). United Nations. https://www.un.org/sites/un2.un.org/files/2021-twg_2-062321.pdf.

level, this is ensured by specific competencies – engineering-economic and engineering-managerial (Table 1). Engineering-economic competencies refer to the ability to use economic knowledge when evaluating the effectiveness of creating new technical and technological systems and their operation. Engineering-managerial competencies encompass the ability to organise an active innovative process, implement necessary organisational changes and a suitable corporate culture, manage the life cycle of technological systems, improve internal and external communications, work with personnel, and determine priorities for resource allocation while considering stakeholders' interests. For convenience, the term 'technical and economic competencies' will be used further in this article to denote the mentioned groups of competencies.

It should be noted that interdisciplinary competencies do not arise solely from a good command of the disciplinary knowledge from all academic courses; important additions are necessary for their mastery:

1) Academic disciplines that elucidate the interconnections between different fields of knowledge and provide tools for their integration and practical application in project tasks;
2) Research experience on interdisciplinary topics and problems that demonstrate the essence and importance of interdisciplinary connections and relationships;
3) Practical application of interdisciplinary knowledge to solve real business problems, through which they are transformed into managerial competencies.

Table 2
Implementation of a multidisciplinary approach to the training of managers

Goals of professional training	Areas and methods for mastering interdisciplinarity
Students of management – Mastering basic knowledge – Ability to apply it in non-standard situations	Areas of new scientific and technological achievements, sector-specific technologies, and understanding of changes in the content of managerial activities Organisation of R&D using knowledge from various fields Development of systemic, conceptual, strategic, and value-based thinking Conceptual design Business games and teamwork
Lower-level managers – Understanding managerial tasks and basic management systems – Ability to solve non-standard tasks at their level – Ability to work with people and small groups – Mastering the fundamentals of value-based thinking	Demonstration of the multifaceted and complex nature of management knowledge (for engineering graduates) Learning from best practices through the analysis of specific situations Business games, strategic sessions, and teamwork in solving engineering and management tasks
Middle-level managers – Ability to solve non-standard tasks at their level, analyse problem situations, formulate and solve problems – Development of systemic thinking	Integration of management knowledge into a cohesive system Learning from best practices through the analysis of specific situations Conceptual design of development tasks within one's area of activity Business games, strategic sessions, and teamwork in solving innovative challenges
Top managers – Ability to integrate economic, industrial, environmental, political, and cultural goals and solve complex integrated problems – Identify and develop growth points, build breakthrough teams; organise large-scale transformations	Formation of a vision for the future Methods for generating business ideas Behaviour in extreme situations Development of the ability to change vision, strategy, and task priorities Conceptual design of the future Business games, strategic sessions, and teamwork in addressing strategy development and implementation tasks

The goals and methods of interdisciplinary training for managers at different levels of responsibility vary. For lower-level managers, the most important aspect is understanding the interconnections between management systems and the ability to solve atypical tasks. For top managers, priority lies in forming a comprehensive vision for the future, developing competencies for large-scale transformations, managing human capital, and transforming strategic priorities (see Table 2). As shown in the table, the range of interdisciplinarity increases.

Complex problems cannot be solved by simply breaking them down into tasks and assigning responsibility to those with the necessary professional competencies. Non-linear interactions, variability of the system and external environment, and conflicts of interest among stakeholders often mean that it is not even possible to determine what would be considered a successful solution. To manage unpredictable situations, it is essential to maintain a holistic focus on the problem and evaluate the solution as a whole over the entire lifecycle of the system. This requires in-depth knowledge across various fields. Furthermore, science often lacks answers to emerging challenges, necessitating knowledge gained from practice and the ability to generalise accumulated experience in systemic solutions. Interdisciplinary teams can effectively tackle these difficulties, provided there are effective communications and streamlined interactions among team members.

It is also important to emphasise that there is a growing demand for managers, engineers, economists, IT specialists, and professionals from other fields who can work as part of a cohesive team, which implies having a shared conceptual language, a holistic vision of the area for improvement, and proficiency in the tools and methods of systems analysis. In this regard, all team members should possess engineering and economic competencies, albeit with varying degrees of knowledge in areas such as technology, economics, finance, and investment.

For successful actions, members of an interdisciplinary team require knowledge that extends beyond their professional field. To ensure productive interaction, it is necessary to acquire at least a basic level of understanding in related areas, learn to comprehend colleagues with different perspectives, and possess intellectual flexibility, creativity, and the ability to engage in dialogue and collaboration.

Let's take an example from the energy sector. In general, it can be noted that trends in the evolution of the engineering and economic competencies of specialists in this industry are influenced by several factors:

1) the development of energy markets and increased competition;

2) electrification and the displacement of hydrocarbon fuels (the energy transition);

3) the implementation of smart energy systems;

4) the diversification of business and the development of economic relationships between energy suppliers and consumers.

This involves the strengthening and new forms of technical and economic connections within the 'supplier – consumer' framework, including parameters such as the quality and reliability of energy supply (information exchange, mutual financial responsibility for reliability and quality, new economic methods of managing reliability and production efficiency, particularly various demand management mechanisms). The focus of economic activity, not only in the energy sector but also in many other areas of the economy, is shifting from the production-operational framework to a service-oriented one, where polycentric platform-based interactions between market participants are becoming increasingly important.

As a result, the formation of costs and outcomes will become more multi-faceted, and understanding

Fig. 7. Interdisciplinary solutions bring together managers, engineers and economists

interdisciplinarity will become an essential component of systems literacy. For instance, in the promising field of demand-side energy management, the content of engineering and economic competencies will be defined by the need for the following solutions (Table 3).

In a number of studies [Gitelman et al., 2023a; Gitelman, Kozhevnikov, 2023], we have thoroughly outlined the necessary conditions for the 'reset' of engineering-economic education. These include: the revival of engineering-economic faculties; mandatory mastery of the methodologies and experience of systems engineering as the core of fundamental training; a transition to specialised programmes; and a sharp increase in the volume of practical work within the curriculum of relevant programmes. However, an equally important condition is the radical revision of the forms, principles of organisation, and methods of the educational process [Bogomolov, 2022; Ermolov, 2022]. In this context, advanced training is becoming highly relevant – a technologically organised process of acquiring knowledge and competencies to solve future tasks aligned with global trends and national development programmes. It is worth noting that advanced training is carried out using the latest tools, including digital resources, which enable the flexible design of programmes that enhance the attractiveness of professional activities for young people and engage students in addressing current challenges.

The experience of the Department of Energy and Industrial Enterprise Management at Ural Federal University in implementing advanced engineering-economic education demonstrates the high effectiveness of its technological organisation [Professionals in Competition, 2021]. Among the actively developed

Table 3
Technical and business skills in implementing demand-side management programmes

Type of solution	Examples of solutions	
	At the energy company	At the consumer's
Engineering	Assessment of growth opportunities, manoeuvrability, and capacity of generating equipment Changing the mode of power plant operation in the energy system and the structure of generating capacities (e.g., refusal to commission expensive peaking capacities or increase the capacity utilisation factor of base power plants) Reducing the amount of grid capacity redundancy Introduction of load telecontrol and information technologies in the 'supplier-consumer' loop	Switching units to the 'consumer-controller' mode Forcing the unit's performance in the hours of load drop Changing equipment repair schedules Organisation of night shifts
Economic	Planning and evaluation of energy and capacity savings based on the results of demand management programmes implementation Saving of current costs and capital investments in new capacities, especially peaking ones. Budget and programme efficiency Mechanism of economic motivation of consumers	Cost analysis of changes in power consumption modes Results and efficiency taking into account preferences provided by the energy company related to reduced payments for electricity and capacity
Managerial	Designing programmes for design management Coordination of programme implementation schedule with authorities, energy service companies, equipment suppliers Development of incentives for programme participants	Institutionalisation of participation in demand management programmes (preparation of internal regulatory framework, regulations, responsible persons, adjustment of business processes, etc.)

technologies directly used for mastering the systems approach and systems literacy are:

- a digital database of engineering-economic knowledge, which stimulates self-learning and allows for targeted searches for books, articles, and analytical reports by department lecturers for project-research work (Fig. 8);
- virtual tours of leading industrial enterprises to study the technical aspects of complex systems based on their digital twins;
- conceptual design of innovative transformations using a reference model of organisation and continuous project-research work in collaboration with lecturers and external experts.

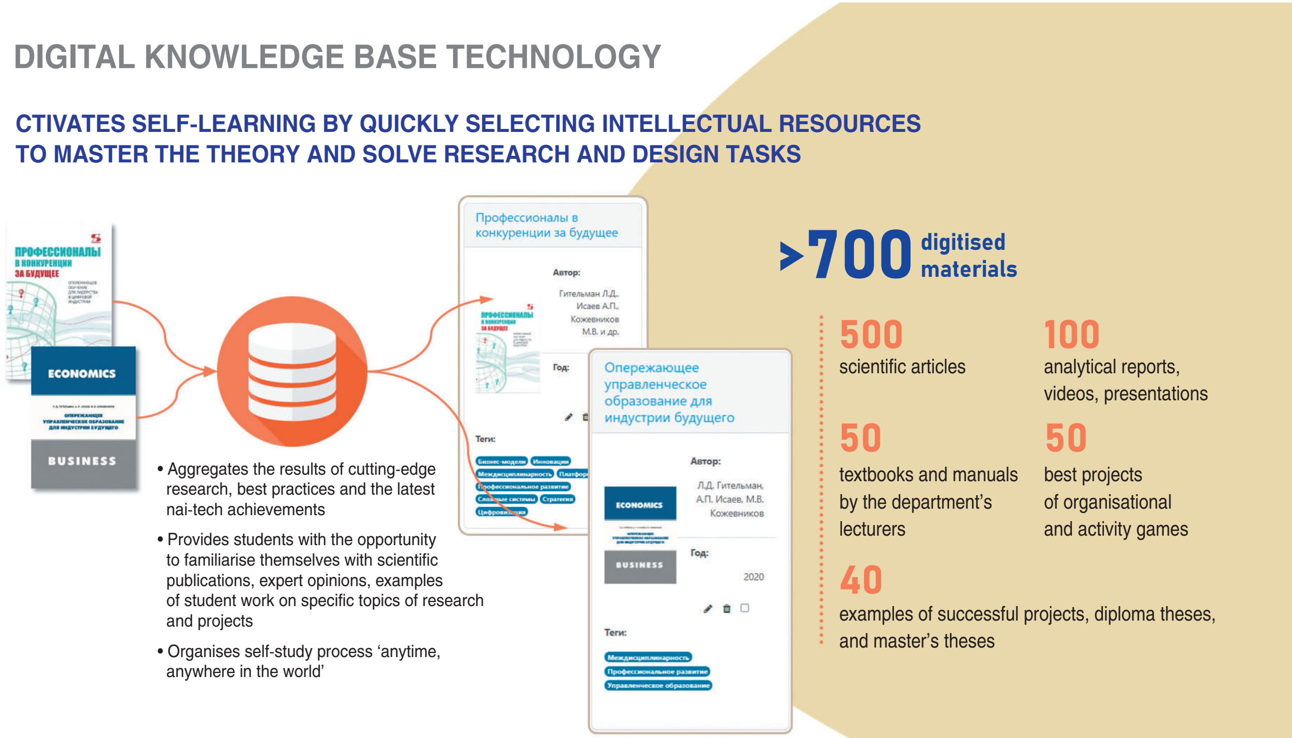
Conclusion

Modern engineering developments represent complex systems and systems of systems, which are based on the interaction of components of various natures and continuously improve throughout design and operation. In the creation of such systems, the interaction between the technical-technological factors of production and the man – their knowledge, skills, and values – is becoming increasingly important, with engineering and humanitarian aspects needing to complement rather than contradict one another. A holistic view of systems, the ability to predict their behaviour under uncertainty, and the organisation of their development and operation in a way that meets the interests of diverse stakeholders – collectively referred to as systems literacy – becomes an essential attribute for managers, engineers, and teams involved in innovative activities.

In the processes of comprehensive modernisation and import substitution, the demand is not only for breakthrough innovations but particularly for their rapid scaling (i.e., organising mass production under resource constraints). The tasks of bringing the latest products and technological solutions to market and energising the innovation process lie within the remit of managers who lead teams and work alongside engineers, economists, and IT specialists. Therefore, in these new realities, systems literacy focuses on understanding interdisciplinary connections and the impact of technologies on the economic, financial, investment, environmental, and social outcomes of enterprises. This significantly highlights the importance of engineering-economic competencies – the ability to evaluate the economic efficiency and market potential of newly developed engineering and technical systems. The issue of accelerated training of personnel with such competencies, under the necessity of achieving technological sovereignty, takes centre stage.

At the same time, systems literacy becomes an integral part of basic engineering-economic training. It enables individuals to perceive systems in the surrounding world (to interpret and evaluate ongoing events through the lens of systematic thinking), to detect and identify patterns

Fig. 8. Visualisation of the Digital Knowledge Database technology



in the dynamics of systems' behaviour, to use acquired knowledge and observations to solve emerging problems and take advantage of arising opportunities, and to learn from experience by adjusting knowledge and actions in line with changes in context and the market environment of the system.

The experience of understanding and developing systems thinking, forming a systemic worldview, and practically applying the systems approach has been accumulated through systems engineering. The tried-and-tested methodologies for overcoming complexity and ensuring adaptability and flexibility in designed systems can be widely used in management, with adjustments for the nature and character of the problems being addressed. Thus, a mandatory condition for the 'reset' of engineering-economic education is the mastery of systems engineering methodologies and experience as the core of fundamental training.

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