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EDUCATION 4.0: INNOVATIVE APPROACHES TO COMPETENCE DEVELOPMENT IN DIGITAL ORGANIZATIONS

Purpose. Development of scientifically based concepts for the development of enterprise personnel competencies within the context of digital transformation.

Methodology. The study is based on a comprehensive interdisciplinary approach, which includes the analysis of scientific sources, methods of predictive analysis, scenario modeling and comparative analysis. The methodology of systems analysis was applied to determine the relationships between technological changes and organizational knowledge and competency needs. Content analysis of scientific literature and digital learning practices was used to develop structured approaches for organizing continuous competency development in digital organizations.

Findings. The concept of employee competence development has been substantiated through innovative approaches dictated by Education 4.0, which is based on the following key principles: forecasting needs in knowledge and competencies, implementing knowledge-based digital twins, creating self-learning ecosystems and integrating artificial intelligence into knowledge management processes. Three innovative concepts of continuous learning were developed: integrative digital andragogy, workflow-integrated microadaptive learning, and ecosystem-based development of transversal competencies. It has been proven that their application allows adapting to the requirements of digital transformation, developing the intellectual potential of enterprises through personalized and adaptive educational strategies.

Originality. Theoretical and methodological foundations for the development of competencies in digital organizations have been developed, which take into account the dynamic updating of new competencies and the integration of intelligent technologies. New approaches to the organization of continuous learning based on digital andragogy, adaptive microlearning, and cognitive profiling of competencies have been proposed. A model of microadaptive learning has been proposed, which allows for the operational updating of knowledge in response to the digital transformation of the enterprise. Additionally, this study expands the concept of competence development in the context of Education 4.0 through the use of artificial intelligence and Big Data in predicting the required knowledge and competences of employees.

Practical value. The practical significance of the results obtained lies in the possibility of their application by enterprises at different levels of digital maturity to develop knowledge management strategies that will meet the requirements of Education 4.0. The proposed concepts can be used to create corporate learning platforms, integrate adaptive learning modules into production processes, as well as to form personalized educational trajectories of employees.

Keywords: *Education 4.0, microadaptive learning, digital andragogy, development of transversal competencies*

Introduction. In today's digital transformation of enterprises, continuous training and development of personnel play a key role, ensuring the adaptability of organizations to a dynamic environment. Technological changes are occurring at an unprecedented rate, and traditional approaches to knowledge management are losing their effectiveness, because traditional learning models do not take into account new realities, including the rapid development of artificial intelligence, big data, blockchain technologies and metaverses. As a result, employees often do not have time to absorb new knowledge and adapt to changes, which negatively affects the productivity of enterprises and their innovative potential. An enterprise's ability not only to adapt to changes but also to anticipate them, forming strategies for the development of intellectual potential, becomes a critical condition for competitiveness. In this context, the development of innovative educational concepts that are able to provide advanced knowledge management, integration of learning into the work process, and the use of digital technologies to personalize educational trajectories deserves special attention.

The introduction of digital technologies into the educational process of enterprises is changing traditional paradigms of professional development. The concepts of proactive knowledge management, adaptive learning, digital andragogy, microadaptive learning, and an ecosystem approach to the formation of competencies are coming to the fore. At the same time, digitalization creates new challenges that require the development of methodological foundations for the formation of educational ecosystems that are able not only to respond to technological changes, but also to proactively shape the future competencies of employees.

Therefore, the relevance of this study lies in the need to develop theoretical concepts for the modern requirements of Education 4.0, theoretical justification and development of innovative approaches to continuous training of employees and the development of their innovative competencies in the context of digital transformation of enterprises.

Literature review. Studies of professional literature and practical cases of modern enterprises demonstrate the growing interest of scientists and practitioners in the issues of innovative development of employee competencies, which are dictated by Education 4.0 and are in demand in digital organizations. Both domestic and for-

eign theorists and practitioners are working on the issue, each of whom focuses their attention on revealing narrow issues of this area of research. The increased attention of scientists and the growing number of scientific works in this scientific area indicate its growing relevance. After all, today enterprises are actively implementing digital technologies in their activities. However, employee knowledge and skills often do not meet the requirements of digital enterprises. Under such conditions, there is an imbalance between the growing level and scale of implementation of digital technologies at enterprises and the growth of the level of education, knowledge and competencies that are necessary for work in digital companies. That is, the development of Industry 4.0 has not only provided technological opportunities for enterprises to digitalize, but also laid the foundation for the development of Education 4.0 to ensure a balance between these interconnected components. The development of Education 4.0 is closely related to the transformation of traditional approaches to learning and the need to form new digital competencies. The foundations of the educational process are revealed in classical works, in particular Bloom's taxonomy of educational objectives [Bloom, B. S., Krathwohl, D. R., 1984], which became the basis for further development of learning models. The theoretical basis for innovative approaches to education is Mezirow's theories of andragogy [Mezirow, J., 1981] and Jarvis's concept of lifelong learning [Jarvis, P., 2009]. Modern educational systems actively integrate digital technologies and adaptive learning [Brusilovsky, P., Peylo, C., 2003], using connectivism approaches as a new educational paradigm [1, 2].

Scientists pay special attention to the connection between Education 4.0 and Industry technologies. 4.0. Smart Factory concept [3] and the development of digital enterprises [4] demonstrate the need to train a new generation of professionals with deep knowledge of the digital economy. The study of IT company business models [5] also highlights the role of digital competencies in modern organizations.

Considerable attention in the literature is paid to knowledge management as a component of organizational strategy development and innovation [6, 7]. In developing this issue, scientists emphasize the role and significance of knowledge management, organizational learning in increasing the efficiency of the organization [8, 9]. In particular, a team of researchers [10] revealed knowledge management as a factor in the formation and implementation of the organization's strategy. The role of the green economy and sustainable development in the context of knowledge management is relevant [11, 12].

A separate vector of research directly concerns Education 4.0. In particular, E. Mukul and G. Buyukozkan [13] conducted a systematic review of the digital transformation of education, and M. Sony and K. Karingada [14] outlined the critical factors for the successful implementation of Education 4.0. Innovative technologies such as generative AI, digital twins [15], SmallTalk AI [16], serious games [17], and 5G technologies [18] play an important role in ensuring individualized and effective learning and developing in-demand competencies. In particular, Y. Lin, et al. [15] highlighted that Fourth Industrial Revolution (4IR) technologies, such as cloud computing, machine learning, and artificial intelligence, have increased productivity but exacerbated the challenges of training and retraining workers. In their study, they introduced the Multi-Fidelity Model Digital Twin, which reconciles the complexity of Digital Twin with Bloom's Taxonomy [1], providing a scalable educational structure. Scientists Malik M., et al. [19] in their study note that firms must create digital strategic flexibility and the key to this is technological education focused on creativity in the era of Industry 4.0 [20]. In this context, the internationalization of higher education in the new reality will be of great importance [21].

Thus, the analyzed sources demonstrate the multifaceted nature of scientific views on knowledge management, competence development, and the implementation of new technologies in accordance with the requirements of Education 4.0 and Industry 4.0. However, the scientific literature has not yet sufficiently explored how digital transformation affects educational approaches in organizations, what mechanisms are most effective for increasing the level of employee competence, and how the combination of individual and collective learning can contribute to the development of the enterprise's intellectual capital.

Unsolved aspects of the problem. However, despite a significant amount of scientific research related to knowledge management, digital learning, and concepts of continuing education in the context of Education 4.0, a comprehensive approach to the formation of integrated models of personnel development in the context of enterprise digitalization has not yet been developed. In particular, the following aspects remain insufficiently researched:

1) predictive knowledge management: using artificial intelligence and Big Data for analyzing trends, weak signals and predicting future needs in knowledge and competencies; scenario modeling based on big data for forming alternative development strategies; implementation of knowledge digital twins, which analyze in real time the impact of new knowledge on the organization's business processes;

2) dynamic knowledge ecosystems: creation of self-organizing knowledge management systems that automatically update information and adapt to changes; implementation of distributed knowledge bases based on blockchain technology to ensure transparency, relevance and reliability of information; use of knowledge metauniverses that allow modeling of future scenarios in a virtual environment;

3) intelligent neural network learning platforms: the use of intelligent learning algorithms that recognize knowledge gaps and form individual educational trajectories for knowledge seekers; the use of neural interfaces that accelerate human interaction with knowledge systems and simplify cognitive processes; gamification of learning based on user behavior data to increase motivation;

4) collective intelligence and knowledge decentralization: the use of crowdsourcing platforms that combine the knowledge of experts in global communities; the development of DAO (Decentralized Autonomous Organizations) for knowledge, where decision-making is based on decentralized consensus; the use of cognitive AI assistants that work as personal "advisors", analyzing the individual thinking style and level of knowledge of their seeker.

These challenges require scientific justification and the development of an integrative methodology that will ensure effective knowledge management and competence development in the context of digital transformation of enterprises. The lack of coordinated strategies and models of continuous learning makes it impossible to fully realize the potential of digital technologies in the field of personnel management and reduces the competitiveness of organizations.

Purpose. The research is aimed at forming methodological approaches to the implementation of proactive knowledge management, the integration of digital educational platforms into production processes and the creation of flexible mechanisms for the development of employee competencies. The results of this work will allow forming the basis for strategic knowledge management, which will contribute to increasing the efficiency of digital transformation of enterprises and the development of their intellectual potential.

Methodology. The methodology of the study is based on an interdisciplinary approach that combines analytical, predictive and empirical methods for studying proactive knowledge management in the context of digital transformation of organizations. The study includes two key stages.

The first stage involved a theoretical analysis of the scientific literature covering classical and contemporary concepts of knowledge management, digital andragogy, and innovative educational technologies. Key principles of forecasting, decentralization, personalization, and integration of educational practices into production processes were identified.

The second stage involves the development of a conceptual model of advanced knowledge management, which is based on three innovative approaches: integrative digital andragogy, micro-adaptive learning in the workflow, and ecosystem-based development of transversal competencies. The specifics of digital, smart, and virtual enterprises are taken into account, which allows adapting educational strategies according to their technological needs.

The results of the study confirm the effectiveness of the developed concepts in increasing the adaptability, cognitive mobility, and competitiveness of organizations in the digital age.

Findings. Currently, the problem of developing a methodology for advanced knowledge management and dynamic updating of new knowledge by employees is extremely relevant. The pace of technological change is so rapid that traditional reactive management models are losing their effectiveness. Fundamentally new approaches are needed that are able not only to adapt to changes, but also to predict them, to form advanced strategies for the development of intellectual potential. Consequently, the problem of developing innovative concepts for the development of competencies and a methodology for advanced knowledge management in an organization, which would be based on the following principles (Fig. 1), is extremely relevant.

An organization's intellectual potential development strategy, built on these principles, will ensure high adaptability and ability to anticipate changes, automatic updating and self-learning of organizational knowledge systems, the formation of proactive strategies for developing intellectual capital, and increasing the competitiveness of organizations through the innovative use of knowledge.

However, using all the advantages of modern digital technologies is impossible without forming a new type of digital literacy of employees, their ability to permanent learning and adaptation in conditions of high uncertainty. Specialists and scientists have developed the following concepts of continuous education:

1. The concept of "lifelong learning" was developed by Peter Jarvis, Knud Illeris and Alan Tate. It is an approach to education that views learning as a continuous process throughout a person's life, not just in formal educational institutions. The concept emphasizes the importance of continuous development of knowledge and skills in different contexts (formal, non-formal, informal) for personal growth and professional adaptation to changes in society and the labor market.

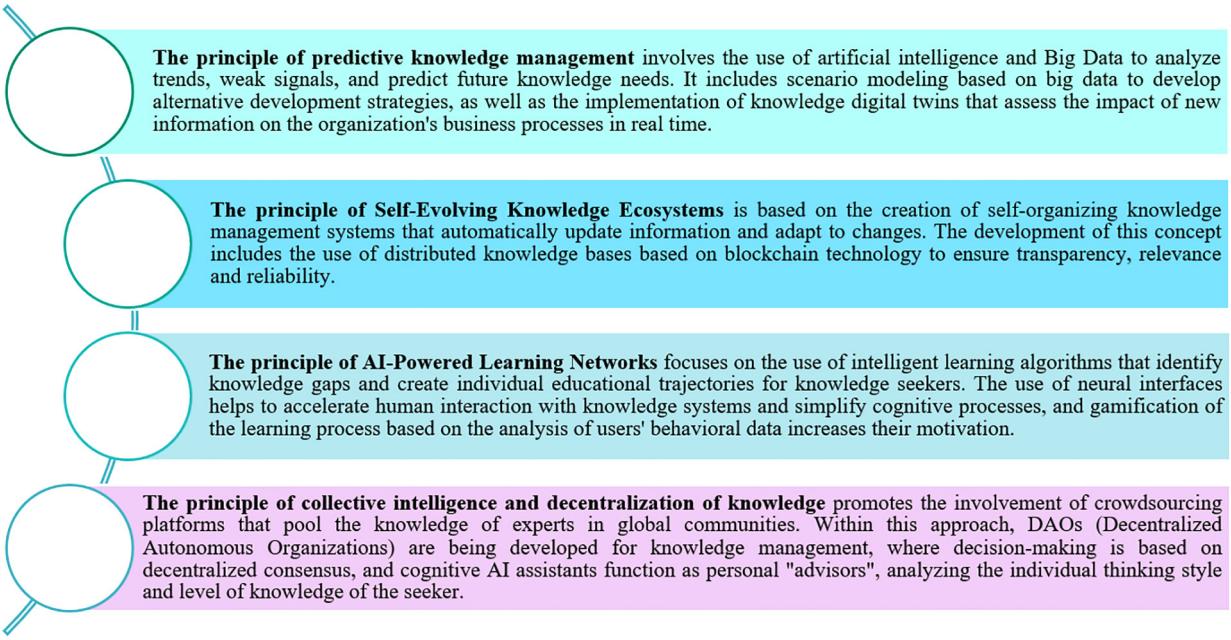

Fig. 1. Principles of developing a methodology for proactive knowledge management in an organization

2. Connectivism Theory in Digital Learning. Developed by George Siemens [2] and Stephen Downes [1]. This theory views learning in the digital age as a process of creating networks and connections between different sources of information. According to connectivism, knowledge is distributed in networks, and learning is a process of connecting to and navigating between these networks. The theory emphasizes the importance of the ability to find, evaluate, and use information in a dynamic digital environment.

3. The concept of transformative adult learning. Developed by Jack Mezirow. This concept focuses on how adults change their established views, beliefs, and perspectives through critical reflection. Transformative learning occurs when a person is confronted with a "disorienting dilemma" that forces them to rethink their assumptions and worldview, leading to profound personal change and a new understanding of themselves and the world.

4. The 70:20:10 Model for Workplace Learning. Developed by Morgan McCall, Michael Lombardo, and Robert Eichinger (1996). According to this model, 70 % of professional learning occurs through experience and work tasks, 20 % through social interaction and observation of others (mentoring, coaching), and only 10 % through formal training (courses, training). The model emphasizes the importance of practical experience and social learning in professional development.

5. The concept of adaptive learning. Introduced by Benjamin Bloom and developed by Peter Brusilovsky. It is an approach to learning that dynamically adapts learning content, methods, and pace to the individual needs and abilities of the learner. With the development of computer technology, the concept has evolved into systems that use algorithms and artificial intelligence to personalize the learning experience and optimize learning paths for each learner.

The acceleration of the pace of digitalization of all spheres of human life creates the need to form new holistic concepts of continuing education that would take into account the specifics of the digital era and ensure the development of not only professional, but also metacognitive competencies of employees.

The analysis of scientific literature shows that continuing education in the digital age should be based on the principles of adaptability, personalization, multimodality and reflexivity. These principles allow creating educational ecosystems that are able to dynamically respond to changes in the technological and social context, ensuring the continuous development of the human capital of organizations. Based on these principles, we offer the following promising innovative concepts of continuing education:

1. The concept of integrative digital andragogy: involves the deep integration of formal, non-formal and informal educational practices into a single personalized trajectory of employee development. It is based on the understanding of adult learning as a multidimensional process that occurs simultaneously in physical and digital space, combining structured educational activities with daily experience of solving work tasks.

A key feature of this concept is the introduction of a "metacognitive core" – a set of educational practices aimed at developing the ability of employees to be aware of and manage their own cognitive processes. This involves the use of techniques of reflective analysis, mental modeling and self-monitoring, which allow an individual not only to acquire new knowledge, but also to transform the ways in which it is processed and applied.

Within the framework of the concept of integrative digital andragogy, organizations should create "learning hubs" – physical and virtual spaces where intensive knowledge exchange takes place between different generations of employees, external experts and artificial intelligent systems. These hubs will function as intersections of different types of knowledge – theoretical and practical, explicit and implicit, disciplinary and interdisciplinary – creating conditions for the emergence of productive cognitive conflicts and insights.

2. The concept of micro-adaptive learning in the workflow: focuses on integrating educational practices directly into the daily activities of employees. Unlike traditional approaches that view learning as a discrete process separated from work functions, this concept involves the creation of intelligent support systems that analyze employee activities in real time and provide contextually relevant knowledge and tools.

Central to this concept are "adaptive microinterventions" – brief educational episodes lasting from a few seconds to a few minutes, activated at moments when an employee is faced with cognitive challenges or potential opportunities for development. These interventions can take various forms: from contextual prompts and recommendations to short simulations or exercises aimed at developing specific aspects of critical thinking or creativity.

Of particular note is the introduction of "social-reflexive circuits" – mechanisms for collective reflection on work experience that allow employees to articulate tacit knowledge, form shared mental models, and develop metacognitive strategies in the process of solving real organizational challenges. These circuits ensure the transformation of individual learning into collective organizational development.

3. The concept of ecosystem-based development of transversal competencies: considers continuing education as a process of development of transversal competencies – universal abilities that allow one to act effectively in different professional and social contexts. These include complex problem solving, systems thinking, intercultural communication, digital literacy, adaptability and ethical leadership.

A feature of this concept is the ecosystem approach, which involves the involvement of various stakeholders (educational institutions, technology companies, public organizations, government agencies) in the creation of integrated educational initiatives. These initiatives are characterized by a high level of interdisciplinarity and combine different learning modalities – from traditional educational programs to hackathons, mentoring projects and communities of practice.

An important component of this concept is "dynamic competency profiling" – an approach to assessing and developing employees' skills that takes into account not only the current level of mastery of certain competencies, but also the potential for their development and combination in non-standard situations. This approach allows for the identification of latent talents and the creation of personalized development trajectories that best

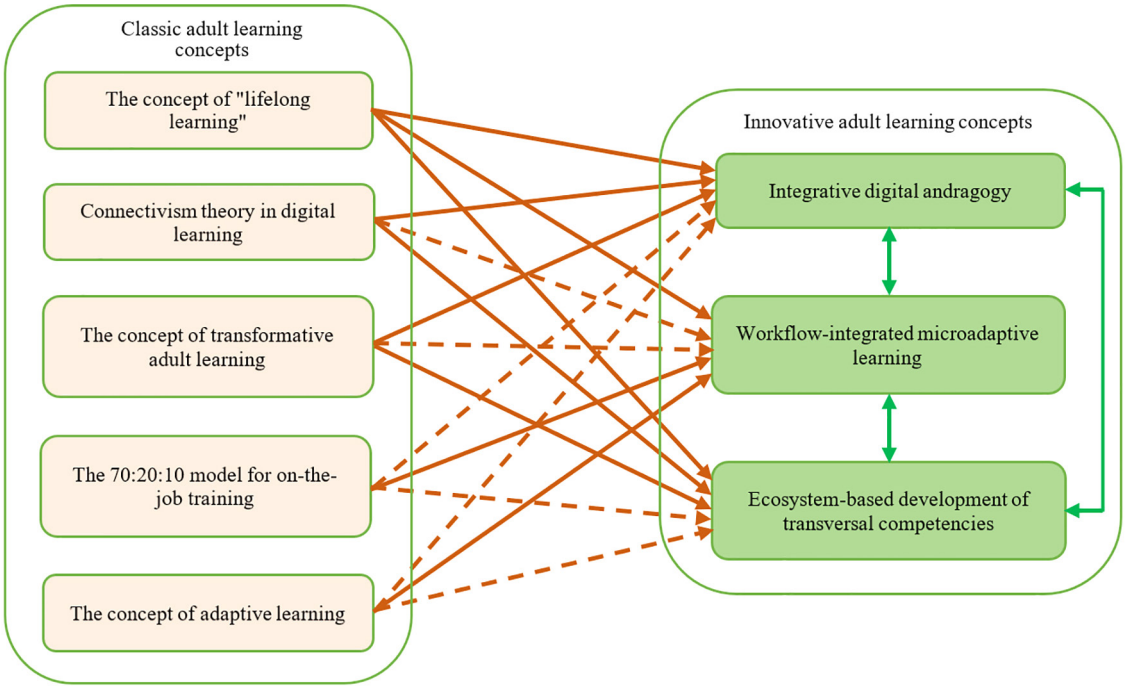

Fig. 2. Diagram of the relationships between classical and innovative concepts of adult education

meet both the individual characteristics of employees and the strategic needs of the organization.

The proposed innovative concepts are closely related to the classical fundamental concepts of continuing education, as demonstrated by the scheme presented in Fig. 2.

This scheme reflects the relationships between classical and innovative concepts of adult education, where:

1) integrative digital andragogy combines elements of:

- lifelong learning (continuity of education);
- connectivism (networked learning in digital space);
- transformative learning (reflection and transformation through the "metacognitive core");
- partly the 70:20:10 model (integration of formal, non-formal and informal practices);
- partially adaptive learning (personalized development trajectories);

2) workflow-integrated microadaptive learning is based on:

- lifelong learning (continuity in the context of work);
- partly connectivism (connections between different sources of knowledge);
- partially transformative learning (through "social-reflexive circuits");
- the 70:20:10 model (on-the-job training);
- adaptive learning (contextual provision of knowledge);

3) the ecosystem-based development of transversal competencies is based on:

- lifelong learning (development of universal competencies);
- connectivism (involving different stakeholders and modalities);
- transformative learning (through interdisciplinary initiatives);
- partially the 70:20:10 model (combination of different learning formats);
- partially adaptive learning (dynamic profiling of competencies).

As can be seen from Fig. 2, innovative concepts are also interconnected:

1. The relationship between integrative digital andragogy and workflow-integrated microadaptive learning:

- complementary perspectives: integrative digital andragogy creates a general framework and philosophy for adult learning in a digital environment, while microadaptive learning offers specific mechanisms for implementing these principles directly into the work process;
- metacognitive practices: the metacognitive core of integrative andragogy provides the basic skills of self-reflection and conscious learning that are necessary for the effective use of adaptive microinterventions in the workflow;
- learning hubs and social-reflexive circuits: learning hubs in integrative andragogy become physical and virtual spaces where social-reflexive circuits of microadaptive learning are formed and function;
- supporting different types of learning: integrative andragogy provides a deep understanding of learning processes, and microadaptive learning ensures its operationalization in specific work contexts.

2. The relationship between workflow-integrated microadaptive learning and the ecosystem-based development of transversal competencies:

- practical application of transversal competencies: microadaptive learning provides specific mechanisms for developing transversal competencies directly during work tasks;
- contextualization of competencies: adaptive microinterventions help employees understand how abstract transversal competencies apply in specific work situations;
- feedback for dynamic profiling: data obtained in the process of microadaptive learning becomes a valuable source of information for dynamic profiling of competencies;
- interdisciplinary application: social-reflexive circuits support the interdisciplinary dialogue necessary for the development of complex transversal competencies.

3. The relationship between the ecosystem-based development of transversal competencies and integrative digital andragogy:

- holistic vision of development: the ecosystem-based development of transversal competencies determines the general directions of employee development, while integrative andragogy provides the methodological foundations for their implementation;
- involvement of various stakeholders: the ecosystem approach expands the concept of learning hubs, involving not only internal but also external stakeholders;
- the connection of competencies with metacognition: the development of transversal competencies (in particular, systems thinking, complex problem solving) is closely related to the metacognitive practices of integrative andragogy;
- personalization and universalization: integrative andragogy offers personalized learning trajectories that, in the context of an ecosystem approach, are aimed at developing universal transversal competencies, creating a productive balance between the unique and the general.

These relationships form an integrated system, where each concept reinforces and complements the others, creating a holistic approach to adult education in the digital age that simultaneously takes into account individual employee needs, organizational requirements, and global trends.

It should be noted that, depending on the depth of transformation, digitalization can be carried out both on a large scale, i.e. of the entire enterprise, and on a partial one – of its individual business processes. Digitization of the enterprise's activities at any level (large-scale or partial) forms a flexible, adaptive, sustainable, customer-oriented and competitive company that provides higher quality services using modern business applications, increasing the client base, expanding the nomenclature and assortment range and scale of activity. Filos E. – an expert in the coordination of ICT projects within the Seventh EU Framework Programme for Scientific and Technical Cooperation, classifies modern "smart enterprises" into three main categories depending on the direction of digital transformations: Digital, Smart and Virtual. Each of these forms is distinguished by specific features that are implemented through the implementation of appropriate software aimed at solving certain tasks and achieving set business goals [3].

A study of the professional literature [3, 22] helped to form the characteristic features of three main types: digital, smart and virtual. After all, their difference lies in the focus of digital changes and the level of integration of ICT into production and management processes.

Digital enterprises are primarily focused on the implementation of digital technologies at the early stages of product development. At the stage of research and creation of new products, computer-aided design and modeling tools are used, which allows you to build digital prototypes, create "digital mockups" and "digital twins". This approach allows you to optimize development, reduce time to market, reduce costs and ensure product individualization in accordance with customer requirements. The main technologies used in such enterprises include CAD/CAM/CAE, product data management systems (PDM), product lifecycle management platforms (PLM) and numerically controlled machine tools.

In turn, *smart enterprises* are focused on mass production while maintaining maximum adaptability and efficiency in management. Such enterprises widely use automation and robotics, thanks to which processes can be carried out without direct human participation. All production elements are combined into a single digital network via next-generation protocols (for example, IPv6), which allows for flexible management. The main technologies here include automated technology management systems, APS planning systems, MES systems, the Industrial Internet of Things (IIoT) and big data analytics.

Virtual Enterprises are the next level of digital evolution, where an integrated network of organizations is formed, including not only production units, but also suppliers, logistics partners and customers. Such enterprises create and use virtual models for both internal processes and for managing global supply chains. This allows for effective coordination of the activities of all production participants, optimize logistics, improve after-sales service and adapt to market changes. Among the main systems used here are ERP, CRM and SCM solutions, which provide end-to-end management of resources, customer relationships and logistics chains.

It is important to realize that different types of "smart enterprises" have their own specific characteristics, strategic goals and technological features, which determine the feasibility and effectiveness of implementing certain educational concepts to develop their intellectual potential. Understanding these relationships will allow enterprises to form optimal approaches to human capital development in the context of digital transformation.

Before proceeding to the justification of the feasibility of implementing specific innovative concepts of continuous learning in different types of "smart enterprises", it is worth outlining a methodological approach to analyzing this relationship. The basis for such an analysis is the identification of key dimensions that determine the compatibility of educational concepts with the characteristics of different types of enterprises.

So, based on the above data, the following key dimensions can be identified for analysis:

1. Technological readiness of an enterprise is the availability of appropriate technological infrastructure, software, and the level of digitalization of processes, which determines the possibility of implementing high-tech educational solutions.
2. The scale and complexity of digital changes is the depth of the transformation of the enterprise's business processes, which determines the requirements for employee flexibility and adaptability.
3. The focus of optimization is the direction of the enterprise's digital transformation (product development, production, or supply chains), which determines the priority areas of personnel development.
4. Organizational structure and culture – features of interaction between departments and employees that influence the forms of organization of educational processes.
5. The level of automation and the role of humans in business processes – the ratio of automated and human-performed processes that determines the focus of educational initiatives.

Using these dimensions, we will analyze the feasibility of implementing various concepts of continuous learning in digital, smart, and virtual enterprises.

Digital enterprises are characterized by the development of models using digital design and modeling tools, the creation of "digital twins" and the release of customized products. Their activities are aimed at increasing the efficiency of all stages of the product life cycle – from research and development to the release of final products. The main systems and technologies of such enterprises are computer-aided design systems (CAD), product data management systems (PDM) and application software for product life cycle management (PLM). Therefore, for digital enterprises, the most appropriate is to implement the concept of integrative digital andragogy.

First, integrative digital andragogy involves a deep integration of formal, non-formal and informal educational practices into a single personalized employee development trajectory that corresponds to the nature of digital enterprises, where research, design and engineering creativity play an important role. Employees of such enterprises must constantly update their knowledge and skills in the field of digital design, modeling and optimization, and this knowledge comes from a variety of sources – both formal curricula and practical experience and independent learning.

Second, a key feature of integrative digital andragogy is the introduction of a "metacognitive core" – a set of educational practices aimed at developing employees' ability to be aware of and manage their own cognitive processes. This is especially important for specialists involved in the development of new products and engineering solutions, since their work requires a high level of creativity, critical thinking and the ability to self-organize. The development of metacognitive skills helps engineers and designers work more effectively with digital models, critically evaluate the results of simulations and find innovative solutions to complex technical problems.

Third, the concept of "learning hubs" – physical and virtual spaces for intensive knowledge exchange – fully meets the needs of digital enterprises in creating an environment for collaborative learning, design and collaborative engineering problem-solving. Such hubs can become a place for the intersection of different types of knowledge – theoretical and practical, explicit and implicit, disciplinary and interdisciplinary – which is critical for the development of innovative products and technologies.

Practical implementation of integrative digital andragogy in digital enterprises can include the creation of internal digital platforms for knowledge sharing, the integration of educational modules directly into design and modeling environments (CAD, PDM, PLM), as well as the organization of collaborative spaces for joint work on projects. An important element is also the implementation of practices of reflective analysis of design and development processes, which will help employees to become aware of and improve their approaches to solving engineering problems.

Implementing this concept in digital enterprises will help create a culture of continuous learning and knowledge sharing, increase employees' ability to adapt in the face of rapid technological development, and ensure more effective use of digital design and modeling tools.

The concept of micro-adaptive learning in the workflow is also highly relevant to digital enterprises, although to a lesser extent than integrative digital andragogy. Its relevance is determined by the following factors:

- digital enterprises actively use complex software systems, working with which requires constant updating of skills and knowledge;

- "Adaptive microinterventions" – short educational episodes activated at moments of cognitive challenge – can be particularly useful when working with digital models and simulations, when employees are faced with new technical problems or atypical software usage scenarios;

- "Socio-reflexive circuits" – mechanisms for collective reflection on work experience – contribute to more effective collaboration between different specialists involved in the product design and development process.

However, in digital enterprises, the implementation of workflow-integrated microadaptive learning may face certain limitations. In particular, design and development processes often require deep focus and continuous work on complex tasks, and in such cases, frequent educational interventions can disrupt the workflow. Therefore, the implementation of this concept should be more balanced and take into account the specifics of specific workflows.

The concept of ecosystem-based development of transversal competencies may also be appropriate for digital enterprises, especially given the need to develop such universal abilities as complex problem solving, systems thinking and interdisciplinary communication. Its appropriateness is determined by the following factors:

- digital enterprises often work on complex engineering projects that require an interdisciplinary approach and involve specialists from different industries. In such conditions, transversal competencies become critical for effective collaboration and coordination of efforts of different teams and departments;

- an ecosystem approach that involves engaging diverse stakeholders in creating integrated educational initiatives can help digital businesses equip their employees with the relevant knowledge and skills needed to work at the forefront of technological development;

- "Dynamic competency profiling" – an approach to assessing and developing skills that takes into account not only the current level of mastery of certain competencies, but also the potential for their development – can be particularly useful for identifying and developing talented engineers and developers capable of generating innovative ideas and solutions.

However, for digital enterprises focused primarily on the technical aspects of product development, implementing this concept may be a lower priority than implementing integrative digital andragogy or microadaptive learning into the workflow.

Smart enterprises are characterized by a focus on mass production of products while maintaining maximum production flexibility, a high level of automation and robotization, and the ability to produce products without human intervention. The main systems and technologies of such enterprises are automated process control systems, synchronous production planning (APS), manufacturing process management systems (MES), Industrial Internet of Things (IIoT) and Big Data analysis technologies. Therefore, for smart enter-

prises, it is most appropriate to implement the concept of micro-adaptive learning in the workflow.

The high level of automation and robotics in smart factories is changing the role of humans in the production process – workers are increasingly performing the functions of setting up, monitoring and making decisions based on data, rather than directly performing production operations. In such conditions, the ability to quickly master new skills and knowledge directly in the context of work situations becomes especially important, which is the essence of microadaptive learning.

"Adaptive microinterventions" – short educational episodes activated at moments of cognitive challenge – are ideal for smart enterprise environments, where workers may encounter new situations and challenges while managing automated systems. Such interventions can provide contextually relevant knowledge and instruction at the exact moment they are needed.

"Social-reflexive circuits" – mechanisms for collective reflection on work experience – can be particularly useful for developing and improving management processes in highly automated production. They allow workers to share experiences in solving non-standard situations, form shared mental models, and develop practices for proactive management of production processes.

Practical implementation of micro-adaptive learning in smart factories can include integrating educational modules into manufacturing execution systems (MES), using augmented reality to provide contextual instructions and information, and creating digital platforms for sharing experiences and best practices between operators of automated systems. Implementing this concept in smart factories will increase the adaptability of employees to new technologies and production processes, ensure more efficient use of automated systems, and reduce risks associated with the human factor.

The concept of ecosystem-based development of transversal competencies is also highly relevant for smart enterprises, although to a lesser extent than micro-adaptive learning in the workflow. Its feasibility is determined by the following factors:

1. Smart enterprises operate in an environment of constant technological change and innovation, which requires employees to develop such transversal competencies as adaptability, systems thinking, and the ability to continuous learning.

2. An ecosystem approach involving diverse stakeholders in creating integrated educational initiatives can help smart businesses equip their employees with relevant knowledge and skills in automation, robotics, and data analytics.

3. "Dynamic competency profiling" can be particularly useful for identifying and developing employees who can effectively manage complex automated systems and make decisions based on big data analysis.

Transversal competencies such as understanding the interrelationships between different technological systems, the ability to interpret data and make decisions under uncertainty, and the skills to communicate effectively across functional units can be of particular value for smart enterprises. An ecosystem approach to developing these competencies can provide a more comprehensive and systematic development of personnel.

The implementation of the concept of integrative digital andragogy in smart enterprises is less of a priority than the implementation of workflow-integrated micro-adaptive learning or the ecosystem-based development of transversal competencies, but still has some potential, especially in the context of training specific groups of employees:

- integrative digital andragogy, with its focus on personalized learning trajectories and the development of metacognitive skills, can be useful for engineers and technicians responsible for the design, implementation, and optimization of automated production systems. For these categories of workers, it is important to develop the ability to think systems, critical analysis, and creative problem solving, which are key elements of the "metacognitive core";

- the concept of "learning hubs" can be adapted to create an environment for sharing knowledge and experience between different functional units of a smart enterprise, which will contribute to more effective coordination and integration of automated processes.

However, for most operators and technicians involved in the direct management of automated systems, it is more appropriate to use workflow-integrated micro-adaptive learning, which provides more targeted and contextually relevant support in the process of performing work tasks.

Virtual enterprises are a network of digital and "smart" enterprises, which also includes suppliers of materials, components and services. They allow developing and using a virtual model of all organizational, technological, logistical and other processes that take place not only at the enterprise, but at the level of distributed production assets and global supply chains. The main systems and technologies of such enterprises are enterprise resource planning systems (ERP), customer relationship management systems (CRM) and supply chain management (SCM). Therefore, for virtual enterprises, the most appropriate is to implement the concept of ecosystem-based development of transversal competencies.

Virtual enterprises function as complex network structures that unite different participants in the production and logistics chain – from raw material suppliers to after-sales service of end users. In such conditions, transversal competencies become especially important, allowing for effective interaction in distributed and heterogeneous teams, understanding the relationships between different elements of the system and making decisions taking into account the global context.

The ecosystem approach, which involves the involvement of various stakeholders in the creation of integrated educational initiatives, fully corresponds to the networked nature of virtual enterprises. It allows for the creation of educational programs and initiatives that take into account the needs and perspectives of all participants in the production and logistics chain.

"Dynamic competency profiling" is particularly valuable for virtual enterprises, as it allows for the identification and development of employees who are able to function effectively in network structures and coordinate the actions of different participants in the production and logistics chain.

Practical implementation of ecosystem-based development of transversal competencies in virtual enterpris-

es may include the creation of inter-organizational educational platforms, joint training programs for employees of different companies participating in a virtual enterprise, as well as the organization of interdisciplinary projects and initiatives aimed at developing cooperation and coordination skills.

The implementation of this concept in virtual enterprises will increase the ability of employees to interact effectively in network structures, ensure more effective coordination of actions of various participants in the production and logistics chain, and contribute to the formation of a common understanding of strategic goals and objectives.

The concept of integrative digital andragogy is also relevant for virtual enterprises, although to a lesser extent than the ecosystem-based development of transversal competencies. Its feasibility is determined by the following factors:

- virtual enterprises operate in a complex information environment where employees must constantly process and integrate information from different sources and systems (ERP, CRM, SCM). In such conditions, the development of metacognitive skills is especially important, which is a key element of integrative digital andragogy;

- the concept of "learning hubs" – physical and virtual spaces for intensive knowledge exchange – can be adapted to create an environment for sharing knowledge and experience between different participants in a virtual enterprise, which is especially important in the context of geographically distributed teams and organizations;

- integrative digital andragogy, with its focus on integrating formal, non-formal, and informal educational practices, can help employees of virtual enterprises effectively process large amounts of information and form a holistic understanding of complex business processes.

Practical implementation of integrative digital andragogy in virtual enterprises may include the creation of inter-organizational digital platforms for knowledge exchange, the implementation of practices of reflective analysis of business processes, as well as the organization of virtual learning hubs for collaboration and joint training of employees of different organizations.

The concept of micro-adaptive learning in the workflow also has some potential for virtual enterprises, although to a lesser extent than ecosystem-based development of transversal competencies or integrative digital andragogy. Its feasibility is determined by the following factors:

- employees of virtual enterprises often interact with complex information systems (ERP, CRM, SCM), and microadaptive learning can help them effectively master new functions of these systems directly in the process of work;

- "Adaptive microinterventions" can be useful to support employees in the decision-making process based on the analysis of data from various sources and systems;

- "Social-reflexive circuits" can promote more effective collaboration between employees of different organizations involved in a virtual enterprise and the formation of joint approaches to solving business problems.

However, for virtual enterprises, which function as complex network structures with numerous participants and processes, the development of a systemic understanding of interrelationships and transversal competencies is more of a priority than spot-on learning in the context of individual work situations. Therefore, microadaptive learning may only be appropriate as a complement to a more systemic approach, such as ecosystem-based development of transversal competencies.

Schematically, the relationships between the three types of "smart enterprises" and the three innovative learning concepts are shown in Fig. 3.

It is important to note that in the real practice of digital transformation of enterprises, hybridization of types of "smart enterprises" is often observed. An enterprise can simultaneously exhibit characteristics of digital, smart and virtual types in its various divisions or processes. In such cases, an integrated approach to the implementation of continuous learning concepts is appropriate, taking into account the specifics of different functional areas and categories of personnel.

For example, a company may have a digital engineering department, smart manufacturing, and virtual partner networks. Such hybridization of the enterprise

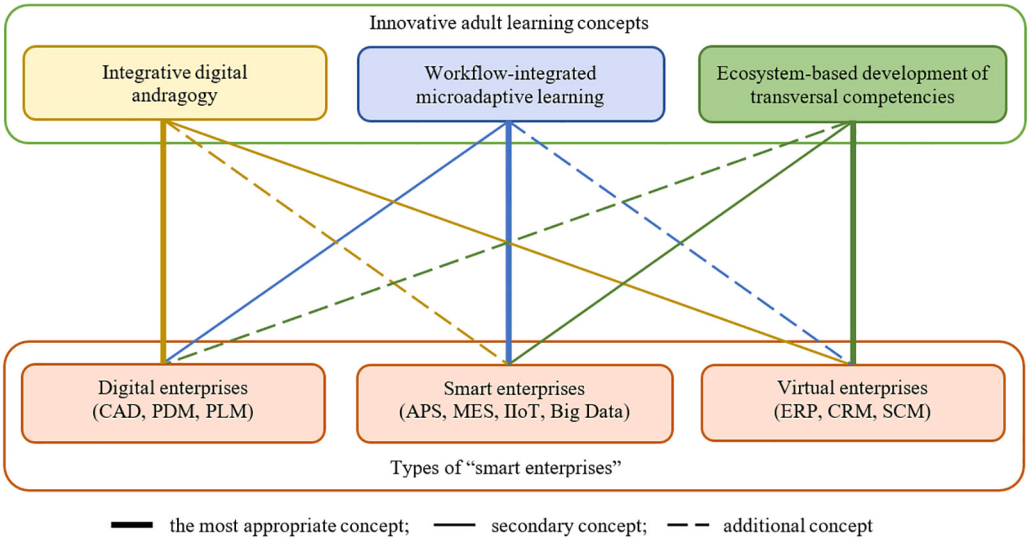

Fig. 3. Diagram of the relationships between types of "smart enterprises" and innovative training concepts

dictates the need for a combined approach to implementing innovative educational concepts. In particular:

- a digital engineering department can use digital andragogy to develop competencies in 3D modeling and digital twins;

- smart manufacturing requires micro-adaptive learning, which allows workers to quickly master new automated technologies.

Virtual interaction with partners requires the development of transversal competencies that ensure effective management of international projects.

Such functional differentiation of educational concepts will allow for flexible adaptation of the learning process to the technological, organizational and individual needs of each unit, which will significantly increase the effectiveness of digital transformation and the development of intellectual capital. Thus, the integration of educational strategies with business models of "smart enterprises" is the key to the success of companies in their future activities.

The proposed innovative concepts of continuous education and the developed recommendations for their application by various types of modern smart enterprises create a theoretical and methodological basis for the formation of flexible, adaptive systems for the development of their personnel, capable of effectively functioning in strategic knowledge management systems of the digital era. Their implementation will allow smart enterprises not only to increase the level of professional competencies of their employees, but also to form a sustainable culture of continuous learning, necessary for successful adaptation to intensive technological and social changes.

Conclusions. In the current conditions of digital transformation of enterprises, the problem of proactive knowledge management and dynamic updating of employee competencies is of particular relevance. Within the framework of the conducted research, a scientifically based concept of knowledge management has been developed, which is based on the principles of forecasting, decentralization, personalization and integration of educational practices into production processes. The scientific novelty of the obtained results lies in the development and theoretical substantiation of innovative approaches to continuous training of employees in the conditions of digital transformation of enterprise activities. Three promising innovative concepts have been proposed: integrative digital andragogy, workflow-integrated microadaptive learning and ecosystem-based development of transversal competencies. These concepts are consistent with classical theories of adult learning, such as "lifelong learning", the theory of connectivism, the 70:20:10 model, the concept of transformative learning and the concept of adaptive learning.

The practical significance of the results obtained lies in the possibility of their use by enterprises of different levels of digital maturity. The proposed educational models are adapted to different types of "smart enterprises": digital, intelligent and virtual ones. Integrative digital andragogy contributes to the development of engineering and research personnel of digital enterprises, microadaptive learning allows for rapid updating of knowledge of employees of smart enterprises, and the ecosystem-based development of transversal competencies ensures effective interaction of participants of virtual enterprises.

The results of the study highlight the importance of adapting educational strategies to technological changes. The implementation of digital platforms, cognitive artificial intelligence, blockchain ecosystems and neural network learning platforms can significantly increase the efficiency of knowledge management and employee competencies. This, in turn, contributes to the growth of the competitiveness of enterprises in the digital era.

Prospects for further research include expanding the empirical base for assessing the effectiveness of the proposed concepts, developing flexible adaptive educational technologies based on artificial intelligence, and developing a methodology for dynamic assessment of competencies in digital ecosystems. Additional attention is required to study the impact of digital transformation on changing behavior patterns and decision-making by employees, which will allow improving human capital management strategies in the context of technological change.

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Освіта 4.0: інноваційні підходи до розвитку компетенцій у цифрових організаціях

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Мета. Розробка науково-обґрунтованих концепцій розвитку компетенцій персоналу підприємств в умовах цифрової трансформації.

Методика. Дослідження ґрунтується на комплексному міждисциплінарному підході, що включає аналіз наукових джерел, методи прогнозного аналізу, сценарного моделювання й компаративного аналізу. Застосована методологія системного аналізу для визначення взаємозв'язків між технологічними змінами й потребами організацій у знаннях і компетенціях. Використано контент-аналіз наукової літератури та практик цифрового навчання, що дозволило сформувати структуровані підходи до організації безперервного розвитку компетенцій у цифрових організаціях.

Результати. Обґрунтована концепція розвитку компетенцій працівників через призму інноваційних підходів, що продиктовані Освітою 4.0, яка базується на таких ключових принципах: прогнозування потреб у знаннях і компетенціях, упровадження цифрових двійників знань, створення самонавчальних екосистем та інтеграція штучного інтелекту у процеси управління знаннями. Розроблені три інноваційні концепції безперервного навчання: інтегративна цифрова андрагогіка, мікроадаптивне навчання в робочому потоці та екосистемне формування трансверсальних компетенцій. Доведено, що їх застосування дозволяє адаптуватися до вимог цифрової трансформації, розвиваючи інтелектуальний потенціал підприємств через персоналізовані й адаптивні освітні стратегії.

Наукова новизна. Розроблені теоретико-методологічні основи розвитку компетенцій у цифрових організаціях, що враховують динамічну актуалізацію нових компетенцій та інтеграцію інтелектуальних технологій. Запропоновані нові підходи до організації безперервного навчання, що базуються на цифровій андрагогіці, адаптивному мікронавчанню й когнітивному профілюванню компетенцій. Запропонована модель мікроадаптивного навчання, що дозволяє здійснювати оперативне оновлення знань у відповідь на цифрову трансформацію підприємства. Крім того, дослідження розширює концепцію розвитку компетенцій в умовах Освіти 4.0 через використання штучного інтелекту та Big Data у прогнозуванні затребуваних знань і компетенцій працівників.

Практична значимість. Практичне значення отриманих результатів полягає у можливості їх застосування підприємствами різних рівнів цифрової зрілості для розбудови стратегій управління знаннями, що відповідатимуть вимогам Освіти 4.0. Запропоновані концепції можуть бути використані для створення корпоративних навчальних платформ, інтеграції адаптивних навчальних модулів у виробничі процеси, а також для формування персоналізованих освітніх траєкторій співробітників.

Ключові слова: *Освіта 4.0, мікроадаптивне навчання, цифрова андрагогіка, формування трансверсальних компетенцій*

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