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CONCEPTUAL MODEL OF A MANUFACTURING ENTERPRISE'S DIGITAL ECOSYSTEM IN THE CONTEXT OF INDUSTRY 4.0

Introduction. The Fourth Industrial Revolution fundamentally transforms the architecture of manufacturing processes. Traditional linear value chains are being replaced by complex network ecosystems. The integration of artificial intelligence, the Internet of Things, blockchain, cyber-physical systems, cloud computing, and digital twins creates a new paradigm of production organisation. The boundaries of individual enterprises blur within the space of distributed collaboration among multiple stakeholders. According to analytical estimates, digital ecosystems generate economic value exceeding tens of trillions of US dollars.

The transformation from vertically integrated structures to participation in digital ecosystems creates significant managerial challenges. Enterprises must balance between control over core competencies and openness to ecosystem interaction. A dilemma arises: whether to invest in proprietary digital capabilities or utilise external platform resources. The integration of heterogeneous technologies is a complex process. Established standards for effectiveness evaluation are absent. Economic objectives must be aligned with environmental and social requirements. These factors shape a new space of managerial decisions.

The Ukrainian context lends particular relevance to this research. Ukraine's IT sector demonstrates resilience even under martial law conditions. Since 2013, IT services exports steadily grew and reached a record USD 7.3 billion in 2022. In 2024, this figure decreased to USD 6.45 billion. Nevertheless, the IT sector remains a key services exporter. In the first half of 2025, it provided over 42% of the country's total services exports [19].

Government and business view digitalisation as a key driver of post-war economic recovery. It serves as an instrument for integration into European digital ecosystems and enhancement of global competitiveness. However, Ukrainian manufacturing enterprises are characterised by a significant digital divide between sectors. Investment in research and development constitutes merely 0.41% of gross domestic product. There is a shortage of highly qualified specialists in digital technologies.

The scientific problem lies in the absence of a holistic conceptual model of a manufacturing enterprise's digital ecosystem. Such a model should organically integrate ecosystem, organisational, and technological levels of analysis. Existing research has limited focus. Some concentrate on theoretical aspects of ecosystems without detailing technological architecture. Others examine Industry 4.0 technological solutions outside the context of ecosystem interaction. Managerial and economic aspects of transformation are often analysed separately from technological ones. This precludes comprehensive understanding of digitalisation processes in manufacturing enterprises.

Analysis of recent research and publications.

The concept of business ecosystems, proposed by Moore J. [8] in 1993, evolved from a biological metaphor to a fundamental theoretical construct in strategic management. Jacobides M. et al. [7] developed ecosystem theory, defining them as a set of stakeholders with varying degrees of multilateral complementarity that are not fully controlled hierarchically. A key characteristic of ecosystems is non-governed interdependence. No single stakeholder can fully control value creation. Instead, it occurs through a complex network of interactions.

Theoretical comprehension of digitalisation's impact on ecosystems gained new momentum in the works of Oberländer A. et al. [9]. The authors proposed OCO Theory (Orientation, Cooperation, Orchestration) – a theory explaining the influence of digital ecosystems on organisational transformation through three mechanisms.

Orientation signifies identifying relevant digital resources within the ecosystem space. The organisation receives orientations for its own transformation amid multiple technological possibilities. Cooperation is realised through the exchange of digital resources between organisations. Common assets and capabilities are formed. Orchestration means recombining existing and acquired resources to create new value. The authors developed a detailed taxonomy of digital resources across five dimensions: resource source, access and control, nature of recombination, competitive advantage, and complementary advantage.



The integration of digital transformation with sustainable development was embodied in the Digital-Sustainability Ecosystem Framework (DSE Framework) presented by Florek-Paszowska A. and Ujwary-Gil A. [4]. The model structures transformation through inputs, five mechanisms, and tri-aspect outputs. Technological and organisational inputs are transformed through five mechanisms. These include efficiency enhancement, dematerialisation, enabling circular economy, accelerating innovation, and digital collaboration. As a result, economic, environmental, and social effects are formed. The model is characterised by adaptive feedback loops. They ensure continuous improvement through monitoring results and tracking environmental changes.

Chen A. et al. [2] integrated the Knowledge-Based View with digital business ecosystem theory, identifying four processes of organisational knowledge base re-configuration. Internal exploitation means reusing existing internal knowledge for digitalising current processes. Internal exploration involves creating new knowledge within the organisation, developing digital innovations. Co-creation with stakeholders occurs through co-innovation with ecosystem partners. The organisation can utilise external ecosystem knowledge by engaging capabilities developed by other participants. Such a matrix emphasises the importance of balance. Successful digital transformation requires combining exploitation of existing knowledge with exploration of new opportunities. It is important to integrate both internal and external knowledge sources.

In the context of the Ukrainian economy, the development of digital ecosystem theory occurs in the works of Blahodyr L. [13] and Nahara E. [18]. Blahodyr L. proposed a typology of digital business ecosystems by value model, scaling direction, and openness level, defining key ecosystem characteristics: modularity, network effects, servitisation, openness, collaboration, customisation, and multilateralisation. Nahara E. developed conceptual foundations and strategic priorities for enterprise digital ecosystem formation, emphasising the necessity of aligning participants' strategies to achieve synergistic effects.

Technological aspects of Industry 4.0 are examined in detail in the work of Hermann M. et al. [6]. The researchers identified six design principles. Interoperability ensures the ability of cyber-physical systems, humans, and smart factories to interact via the Internet of Things. Virtualisation involves creating virtual copies of smart factories through linking sensor data with virtual models. Decentralisation means the ability of cyber-physical systems to make decisions autonomously. Real-time operation involves instantaneous data collection and analysis. Service orientation is realised through service provision by organisations, cyber-physical systems, and humans in the Internet of Services. Modularity ensures flexible adaptation of smart factories to changing requirements. This is achieved through replacing or expanding individual modules.

Industry 4.0 architectural standards, notably the Reference Architectural Model Industrie 4.0 developed by Platform Industrie 4.0 [11], and the OPC UA standard from OPC Foundation [10], form the technological foundation for inter-system communication. OPC UA ensures manufacturer-, platform-, and operating-system-independent communication, which is critically important for integrating heterogeneous equipment into a unified production ecosystem.

Dieguez T. and Machado J. [3] conducted a comprehensive review of manufacturing execution systems in the Industry 4.0 context, emphasising their transformation from simple monitoring systems to intelligent platforms integrating data from planning and control levels. Bakhtiyarov B. et al. [1] proposed an enhanced Super SCADA architecture with integrated predictive analytics, demonstrating the evolution of supervisory control systems from reactive monitoring to proactive management based on artificial intelligence. Gharibvand V. et al. [5] systematised approaches to cloud manufacturing, revealing evolution from traditional cloud services to integrated platforms combining infrastructure, platform, and software as a service.

Works by Ukrainian researchers illuminate the specifics of digital transformation under transitional economy and martial law conditions. Kryshchal H. et al. [16] investigated the impact of Industry 4.0 on the digital transformation of Ukrainian manufacturing enterprises, emphasising enterprise functional subsystems and their digitalisation tools. Barabas D. et al. [12] analysed the digitalisation of Ukrainian companies under wartime conditions, revealing a paradoxical combination of challenges and opportunities: on one hand, infrastructure destruction and workforce migration create obstacles; on the other, martial law accelerates digital solution adoption and stimulates innovation.

Dubnytskyi V. et al. [15] developed methodological aspects of regional digital ecosystem formation, defining key components and participant interaction mechanisms within regional ecosystems. Voronkova V. and Metelenko N. [14] systematised approaches to industrial management digital transformation, emphasising the necessity of transforming managerial practices parallel to technology implementation.

The literature review demonstrates significant developments in digital ecosystem theory and Industry 4.0 technological solutions. However, there is an observable absence of integrated models that would organically combine the ecosystem level of analysis with organisational and technological levels. Theoretical concepts, notably OCO Theory and DSE Framework, are not integrated with practical manufacturing system architecture. The Ukrainian context, despite valuable research, requires systematisation within a unified conceptual model that would account for transitional economy specifics, martial law conditions, and the capabilities of a robust IT sector.

The aim of this article is to develop a multi-level conceptual model of a manufacturing enterprise's digital

ecosystem for effective integration of Industry 4.0 technologies.

To achieve this aim, the following tasks are set:

- to investigate theoretical approaches to digital ecosystems and identify key mechanisms of enterprise integration into the ecosystem based on OCO Theory;
- to develop a multi-level conceptual model of a manufacturing enterprise's digital ecosystem through integration of OCO Theory, DSE Framework, and Knowledge-Based View;
- to substantiate architectural principles of Industry 4.0 technology integration based on six design principles;
- to determine processes of organisational knowledge base reconfiguration in the context of ecosystem interaction.

Digital transformation management and economic effectiveness evaluation are the subject of separate research by the authors.

Presentation of the main research material. This work has developed a multi-level conceptual model of a manufacturing enterprise's digital ecosystem (figure) based on the integration of theoretical approaches – OCO Theory, DSE Framework, and Knowledge-Based View – with Industry 4.0 architectural principles. The model is structured into four interaction levels that form an integrated system with inter-level connections. The ecosystem level of the model is based on the author's previous research on investment climate formation [17], which structures the enterprise's external environment through the microenvironment of direct influence and eight factors of the macroenvironment of indirect influence (political, economic, legal, scientific-technological, socio-cultural, demographic, infrastructural, natural-geographical). This structuring is critically important for understanding the context of digital transformation, as investment attractiveness and external conditions directly influence the possibilities of attracting resources for implementing Industry 4.0 technologies.

The ecosystem level forms the external environment of enterprise operation, encompassing multiple stakeholders and external influence factors [7]. The structure of the ecosystem level is based on the investment climate formation model [17], which includes the microenvironment of direct influence and the macroenvironment of indirect influence.

Suppliers, partners, clients, technology providers, regulators, and research institutes form the stakeholder network of the microenvironment, with whom the enterprise directly interacts in the value creation process. The macroenvironment encompasses eight groups of indirect influence factors [17]: political (state digitalisation policy, geopolitical stability), economic (investment climate, access to financing), legal (regulatory frameworks, notably European Green Deal requirements), scientific-technological (breakthrough technologies in artificial intelligence and quantum computing), socio-cultural (societal expectations regarding corporate social responsibility and ESG standards), demographic (availability of qualified personnel), infrastructural (digital

infrastructure, logistics), and natural-geographical (access to resources, environmental constraints).

The ecosystem level is characterised by bidirectional interaction. Top-down, the ecosystem influences the organisation in several ways. Firstly, it sets orientations for strategy formation. Secondly, it determines which resources and capabilities are available to the enterprise. Thirdly, it shapes expectations regarding standards and practices. The reverse direction of influence – bottom-up – also occurs. Through its activities, the organisation transforms the ecosystem configuration. It generates new resources that become available to other participants. Moreover, it initiates changes in established practices and standards. At the ecosystem level, external knowledge reconfiguration processes are realised: utilising external ecosystem knowledge and co-creation with stakeholders [2].

Based on OCO Theory [9], integration mechanisms have been formulated that connect the ecosystem level with the organisational level. The first mechanism – orientation – helps identify relevant digital resources in the ecosystem space. When the ecosystem influences the organisation top-down, it transmits orientations for its digital transformation. Such orientations include established practices, technological standards, and successful cases. Bottom-up interaction has a different character. The organisation actively searches for necessary resources, identifies potential partners, and analyses ecosystem opportunities.

Cooperation as an integration mechanism ensures the exchange and joint use of digital resources between ecosystem organisations. Digital resources are classified according to five dimensions [9]. The first dimension – resource source – distinguishes assets (materialised objects such as data and infrastructure) and capabilities (organisational abilities, notably analytical competencies or artificial intelligence application). The second – access and control – identifies internal resources fully controlled by the organisation, shared resources with access by several participants, and external resources controlled by other ecosystem participants. The third – recombination – distinguishes resources recombined in production or in consumption. The fourth – competitive advantage – is based on VRIN criteria: value, rarity, inimitability, and non-substitutability. The fifth dimension – complementary advantage – identifies generic, unique, and supermodular resources that create synergy when combined.

The third integration mechanism – orchestration – ensures effective recombination of digital resources for forming new value. In the top-down direction, resource coordination occurs at the ecosystem level. The coordinating role can be performed by a digital platform or leading ecosystem participant. Bottom-up interaction has a different character. The organisation recombines resources to form its own value proposition. New products or services are developed based on available digital ecosystem capabilities.

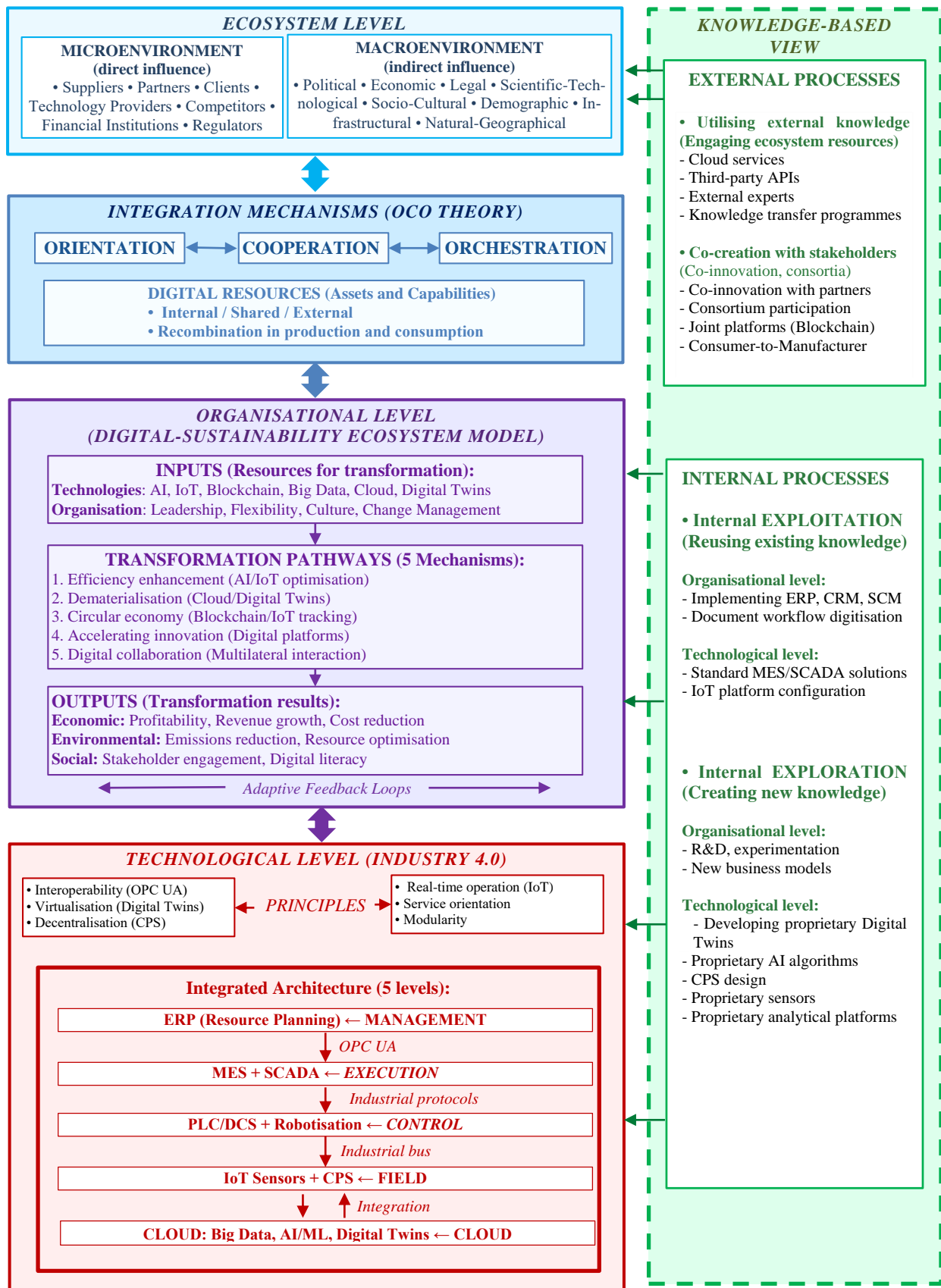


Figure. Conceptual model of a manufacturing enterprise's digital ecosystem in the context of Industry 4.0

Source: developed by the author based on integration of own development [17], OCO Theory [9], DSE Framework [4], Knowledge-Based View [2], Design Principles for Industry 4.0 [10].

The organisational level, conceptualised through DSE Framework [4], structures the enterprise transformation process into three components: inputs, mechanisms, and outputs.

The technological dimension of inputs includes key digital technologies. AI and machine learning open possibilities for predictive analytics and decision-making process automation. Internet of Things technologies, notably in industrial execution (IIoT), enable real-time data collection. Blockchain utilisation ensures operation transparency and process traceability. Big data analytics is applied for decision substantiation. Cloud computing provides access to infrastructure, platforms, and software in service format. Virtual replicas of production processes are created using digital twins. Automation and robotisation enhance overall production efficiency.

The organisational dimension of inputs encompasses five components. Adaptive leadership means management's ability to respond rapidly to changes. Flexible structures are formed through creating cross-functional teams. Inter-functional collaboration helps overcome organisational silos. Digital culture forms the common mindset necessary for innovation. Change management is directed at overcoming transformation resistance.

Five transformation mechanisms [4] form pathways for converting inputs into results. Efficiency enhancement is realised through AI-based predictive maintenance, enabling equipment failure prediction and maintenance planning, real-time analytics for production process optimisation, resource utilisation optimisation, and waste reduction. An implementation example is Siemens' smart energy grids, where sensor integration, analytics, and artificial intelligence ensure energy consumption optimisation and network loss reduction.

Dematerialisation involves transitioning from physical objects to their digital equivalents. Cloud computing eliminates the need for proprietary physical infrastructure. The result is capital expenditure reduction and flexibility enhancement. Digital twins enable virtual testing of production process changes without the necessity of creating physical prototypes. Digital services increasingly replace physical products, transforming enterprise business models. Additive manufacturing serves as a striking example. 3D printing technology ensures local component production based on digital models. Consequently, the need for physical transportation is reduced.

Enabling circular economy occurs through material tracking using the Internet of Things throughout the product lifecycle, blockchain utilisation for ensuring supply chain transparency and confirming material origin, implementing recycling and remanufacturing processes based on component condition data, and creating closed-loop production systems where waste from one process becomes inputs for another.

Innovation is accelerated through various instruments. Digital collaboration platforms enable engaging external partners at the development stage. Open innovation, enhanced by AI, relies on artificial intelligence that analyses external idea sources and identifies promising development vectors. Rapid prototyping relies on Google Design Sprint and Lean Startup methodologies. They reduce time from idea to hypothesis testing.

Digital collaboration as the fifth mechanism is realised through several instruments. Multilateral interaction occurs through platforms coordinating multiple participants' activities. Blockchain-based transparency creates trust between participants without a central intermediary. Real-time data exchange ensures production process synchronisation. Cross-sectoral partnerships enable creating innovative solutions at the intersection of different knowledge domains.

Transformation outputs are measured across three dimensions according to the Triple Bottom Line concept [4]. The economic dimension includes several components. Eco-efficient product design integrates economic and environmental efficiency. Product-as-a-Service business models enable selling product usage rather than the product itself. New revenue streams from digital services and data analytics are formed. Operating costs are reduced through process optimisation. The environmental dimension encompasses several directions. Real-time emissions monitoring ensures regulatory compliance. Resource utilisation is optimised through precise planning. Waste is minimised through better forecasting. Carbon footprint is reduced through logistics and energy consumption optimisation. The social dimension is represented by three components. Stakeholder engagement is strengthened through transparent communications and interaction platform deployment. Employee satisfaction levels increase as routine operations are reduced. Digital literacy development occurs through training systems and upskilling programmes.

The organisational level is characterised by adaptive feedback loops. IoT monitoring ensures real-time data collection on transformation results. Organisational learning relies on systematic analysis of previous experience, laying the foundation for future strategies. Strategy adjustment enables adapting transformation directions considering achieved results. During next steps planning, external influences are considered – changes in regulatory frameworks, consumer expectations, and technological environment.

The technological level is based on six Industry 4.0 design principles [6] and is realised through integrated manufacturing system architecture. Interoperability is ensured by the OPC UA standard [10], enabling heterogeneous systems to exchange data independently of equipment manufacturer or software platform. Standardised protocols, notably APIs and web services, ensure seamless communication between cyber-physical systems, the Internet of Things, and cloud services.

Virtualisation is implemented by developing digital twins of production processes. This enables testing changes in a virtual environment before they are implemented in actual production. Virtual space modelling enables assessing alternative scenarios' impact on process efficiency. Simulation technology is applied for optimising production planning, logistics flows, and equipment layout.

Decentralisation means that cyber-physical systems can make autonomous decisions based on locally available information. Edge computing shifts computational power closer to data sources. Consequently, latency is reduced and real-time decision-making capability is created even when connection with central systems is absent. Distributed architecture makes the system more resilient to individual component failures.

Real-time operation is ensured by three components. Firstly, IoT sensors collect data at a frequency enabling immediate deviation detection. Secondly, real-time analytics processes data streams and identifies patterns. Thirdly, decision support systems generate action recommendations immediately upon problem detection.

Service orientation means providing functionality through services. The Internet of Things enables equipment to provide services to other systems. Cloud services are realised in three models: SaaS, PaaS, and IaaS. This provides access to software, development platforms, and computational power without the need for ownership of these resources. Digital platforms consolidate numerous participants who jointly generate value through service integration.

Modularity consists in constructing production systems from interchangeable modules. This enables flexibly changing configuration depending on needs. Rapid change adaptation is realised through the plug-and-produce concept. New equipment is automatically integrated into the system. Lengthy configuration is not required.

The integrated architecture is structured into five levels [11]. The management level includes three system types. These include Enterprise Resource Planning (ERP) systems, Supply Chain Management (SCM), and Customer Relationship Management (CRM). They ensure strategic and tactical activity planning. The execution level includes three system types. Manufacturing Execution Systems transform from simple monitoring tools to intelligent data integration platforms [3]. Supervisory Control and Data Acquisition systems evolve to Super SCADA with predictive analytics [1]. Warehouse Management Systems optimise logistics. The control level includes Programmable Logic Controllers (PLC), Distributed Control Systems (DCS), robotic complexes, and automated equipment. The field level encompasses IoT sensors and actuators designed for data collection and command implementation, intelligent machines with IIoT functionality, and cyber-physical systems that integrate physical processes with computational capabilities. The cloud level encompasses cloud manufacturing platforms for accessing production capacities as a

service [5], big data analytics for processing information arrays, artificial intelligence and machine learning as a service, and digital twin repositories for managing virtual models.

The organisational and technological levels are integrated with internal knowledge reconfiguration processes. Internal exploitation at the organisational level involves implementing ERP, CRM, SCM systems; at the technological level – configuring standard MES, SCADA, IoT solutions. Internal exploration at the organisational level is realised through R&D and experimentation with new business models; at the technological level – through developing proprietary Digital Twins, AI algorithms, cyber-physical systems, sensors, and analytical platforms.

Organisational knowledge base reconfiguration in the context of ecosystem interaction occurs through four processes [2], integrated with the model's levels. External processes interact with the ecosystem level; internal processes encompass organisational and technological levels. As an external process, utilising external knowledge means engaging resources created by other ecosystem participants. This is realised through several pathways: cloud services with ready functionality are applied, third-party APIs are integrated for accessing platform capabilities, external experts in digital technologies are engaged, and participation in knowledge transfer programmes occurs. Co-creation with ecosystem stakeholders as the second external process is realised through co-innovation with partners, consortium participation for standard development, and creating joint blockchain-based platforms. An example is the Consumer-to-Manufacturer model implemented by Chinese company Wensli, where consumers directly participate in product design through a digital platform [2].

Internal exploitation as an internal process involves reusing existing knowledge for process digitalisation. At the organisational level, this includes implementing Customer Relationship Management systems, Enterprise Resource Planning systems, and document workflow digitisation. At the technological level – implementing standard ERP, MES, SCADA solutions, and configuring IoT platforms.

Internal exploration as the second internal process consists in creating new knowledge within the organisation. At the organisational level, it includes research and development. Experimentation with new business models occurs. Proprietary digital products or services are developed. At the technological level, proprietary digital twins and specialised AI algorithms are created. Cyber-physical systems are designed. Proprietary sensors and analytical platforms are developed. An example is Wensli company, which developed proprietary equipment for digital printing on fabrics.

Conclusions. A multi-level conceptual model of a manufacturing enterprise's digital ecosystem has been developed, integrating four interaction levels with end-to-end knowledge reconfiguration processes. The ecosystem level encompasses external stakeholders and in-

fluence factors. Integration mechanisms based on OCO Theory include orientation, cooperation, and orchestration. The organisational level is structured through DSE Framework with inputs, five transformation mechanisms, and tri-aspect outputs. The technological level is based on six Industry 4.0 design principles and a five-level integrated architecture. The Knowledge-Based View is integrated with all levels: external processes (utilising external knowledge, co-creation) interact with the ecosystem level; internal processes (exploitation, exploration) encompass organisational and technological levels. The model is characterised by the presence of inter-level connections in the format of top-down and bottom-up interactions. This ensures dynamic adaptation to ecosystem changes and organisational capabilities.

Three mechanisms of enterprise integration into the digital ecosystem have been identified and substantiated. Orientation ensures identification of relevant digital resources in the ecosystem space through providing orientations by the ecosystem top-down and active search by the organisation bottom-up. Cooperation realises digital resource exchange between organisations based on taxonomy across five dimensions: source, access and control, recombination, competitive and complementary advantage. Orchestration involves digital resource recombination for creating new value through coordination at ecosystem and organisation levels.

Based on the Digital-Sustainability Ecosystem (DSE) model, five directions of manufacturing enterprise transformation have been identified. The first direction – efficiency enhancement – is achieved through AI optimisation, real-time analytics, and resource utilisation rationalisation. The second direction consists in dematerialisation, when physical objects are replaced by digital equivalents (cloud computing, digital twins, digital services). The third vector – circular economy – relies on IoT material tracking and blockchain-ensured supply chain transparency. The fourth direction involves innovation intensification through digital platforms and AI-based open innovation. The fifth direction is digital collaboration, realised through multilateral real-time data operations.

Architectural principles of Industry 4.0 technology integration have been substantiated based on six design principles and a five-level integrated architecture. Interoperability is ensured by the OPC UA standard, virtualisation – by digital twins, decentralisation – by autonomous cyber-physical systems. Real-time operation is achieved through IoT sensors and analytics, service orientation – through cloud services, modularity – through flexible configuration. The architecture encompasses five levels: management, execution, control, field, and cloud. Integration occurs through standardised protocols.

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Four processes of organisational knowledge base reconfiguration in the digital ecosystem context and their integration with the model's levels have been determined. External processes encompass two directions. The first – utilising external knowledge through engaging ecosystem resources. The second – co-creation through co-innovation with partners. Both interact with the ecosystem level. Internal processes also have two components. Exploitation involves reusing existing knowledge. At the organisational level, these are ERP, CRM, SCM systems; at the technological level – standard MES, SCADA, IoT. Exploration is directed at creating new knowledge. At the organisational level, this is R&D and new business models; at the technological level – proprietary Digital Twins, AI algorithms, CPS, sensors. Balancing all these processes is key to successful transformation.

The scientific novelty of this research lies in the developed integrated conceptual model that organically combines ecosystem, organisational, and technological levels of manufacturing enterprise digital transformation through synthesis of OCO Theory, DSE Framework, and Knowledge-Based View with end-to-end integration of knowledge reconfiguration processes. The model differs from existing ones by the presence of inter-level connections, adaptive feedback loops, and clear linkage of external knowledge processes to the ecosystem level, and internal processes to organisational and technological levels. This ensures dynamic enterprise adaptation to ecosystem changes and holistic understanding of knowledge management processes in digital transformation.

The proposed model has practical significance for enterprises. It ensures strategic planning of digital transformation considering ecosystem context. The model enables determining investment priorities in digital technologies. This is based on Industry 4.0 architectural principles. It provides a systematic approach to integrating heterogeneous Industry 4.0 technologies through five-level architecture. It ensures a foundation for organisational knowledge base reconfiguration through four defined processes.

Digital transformation management, digital maturity assessment, and a multimetric approach to measuring economic effectiveness require separate investigation. This is a promising direction for future work. Other prospects include empirical validation of the model on cases of Ukrainian manufacturing enterprises of various sectors and scales. Sector-specific adaptations of the model are advisable. Creating an integrated digital transformation effectiveness index deserves particular attention.

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Loza S. Conceptual model of a manufacturing enterprise's digital ecosystem in the context of Industry 4.0

This article proposes an integrated model of manufacturing enterprise transformation that synthesises ecosystem interaction logic with technical and organisational aspects of Fourth Industrial Revolution technology implementation. The topic's relevance is determined by the transition from traditional value chains to network forms of collaboration, where enterprises function as participants in complex digital ecosystems. The research addresses how manufacturing organisations can systematically integrate into digital networks whilst simultaneously transforming internal processes and technological infrastructure. The methodological foundation comprises the combination of OCO Theory for ecosystem integration mechanisms through orientation, cooperation, and orchestration of digital resources, DSE Framework for structuring organisational changes across five transformation trajectories with tri-aspect outputs, and Knowledge-Based View for competence reconfiguration processes through external engagement and internal knowledge creation. The proposed model structures interaction across four levels – from the external ecosystem environment with micro- and macro-influence factors through integration mechanisms and organisational trajectories to specific technological architecture of production systems, built on principles of interoperability, virtualisation, decentralisation, real-time operation, service orientation, and modularity. The work's novelty lies in conceptualising end-to-end knowledge management processes that permeate all model levels and ensure bidirectional connection between external ecosystem resources and internal organisational capabilities through mechanisms of exploiting existing competencies and exploring new opportunities. The model is intended for use in strategic planning and can serve as a foundation for making decisions regarding prioritising investments in digital technologies considering ecosystem context and national economy specifics.

Keywords: digital ecosystem, Industry 4.0, digital transformation, manufacturing enterprise, multi-level model, strategic management, knowledge reconfiguration, technology integration, cyber-physical systems.

Лоза С. П. Концептуальна модель цифрової екосистеми виробничого підприємства в контексті Індустрії 4.0

У статті запропоновано інтегровану модель трансформації виробничих підприємств, що синтезує екосистемну логіку взаємодії з техніко-організаційними аспектами впровадження технологій четвертої промислової революції. Актуальність теми визначається переходом від традиційних ланцюгів створення вартості до мережових форм співпраці, де підприємства функціонують як учасники складних цифрових екосистем. Дослідження відповідає на питання, як виробничі організації можуть системно інтегруватися у цифрові мережі, одночасно трансформуючи внутрішні процеси та технологічну інфраструктуру. Методологічною основою слугує поєднання OCO Theory для механізмів екосистемної інтеграції через орієнтацію, співпрацю та оркестрацію цифрових ресурсів, DSE Framework для структурування організаційних змін за п'ятьма траєкторіями трансформації з триаспектними виходами, та Knowledge-Based View для процесів реконфігурації компетенцій через зовнішнє залучення та внутрішнє створення знань. Запропонована модель структурує взаємодію на чотирьох рівнях – від зовнішнього екосистемного середовища з мікро- та макрофакторами впливу через механізми інтеграції та організаційні траєкторії до конкретної технологічної архітектури виробничих систем, побудованої на принципах інтероперабельності, віртуалізації, децентралізації, реального часу, сервісної орієнтації та модульності. Новизна роботи полягає у концептуалізації наскрізних процесів управління знаннями, що пронизують всі рівні моделі та забезпечують двосторонній зв'язок між зовнішніми екосистемними ресурсами і внутрішніми можливостями організації через механізми експлуатації наявних компетенцій та експлорації нових можливостей. Модель призначена для використання у стратегічному плануванні та може слугувати основою для прийняття рішень щодо пріоритетизації інвестицій у цифрові технології з урахуванням екосистемного контексту та специфіки національної економіки.

Ключові слова: цифрова екосистема, Індустрія 4.0, цифрова трансформація, виробниче підприємство, багаторівнева модель, стратегічне управління, реконфігурація знань, інтеграція технологій, кіберфізичні системи.