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AGENT-BASED MODELING IN MULTI-LEVEL INDUSTRIAL ECOSYSTEMS DEVELOPMENT

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ABSTRACT

In industrial ecosystems development, there are currently trends towards deepening vertical and horizontal integration within the innovation processes framework. They entail approaches complication to management functions implementation. Management and development problems solutions in multi-level industrial ecosystems becomes particularly relevant. The study's purpose is to formulate possible approach to such problems solving that can increase management decision-making efficiency. The work proposes simultaneous agent-based modeling and multi-level digital twins use in order to simulate economic processes. The study proposes multi-level industrial systems conceptual scheme for an agent-based modeling, taking into account its' vertically hierarchical structure. The proposed model identifies four levels (with their own agents), differing in the nature of the tasks being solved, the responsibility area, organizational and economic mechanisms used. It is proposed to base the model on economic and mathematical tools, in particular computer modeling methods, creating digital twins specifically. Digital twins are used to analyze production chains, assess internal and external factors effect, develop alternatives and select most preferable solutions to emerge management problems. At the same time, it was determined that digital twins structure should be multi-layered, where each subsequent level incorporates digital twins developed on the previous one, endowed with implemented functions certain set. It is substantiated that one of the important tasks is to determine industrial ecosystem digital twin managerial layer optimal configuration. This layer is responsible for modeling the organizational and managerial component and is built on needs to achieve financial and economic activity target indicators. The study proposes and describes the agent-based model operation mechanism, the development of which is allows to produce management strategies based economic and mathematical modeling complex tools, scenario and forecast analysis and digital twins numerical modeling.

Keywords: Agent-based modeling; Industrial ecosystem; Multilayer digital twin; Digital architecture; Industrial complex.

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MODELAGEM BASEADA EM AGENTES NO DESENVOLVIMENTO DE ECOSSISTEMAS INDUSTRIAIS EM VÁRIOS NÍVEIS

RESUMO

No desenvolvimento de ecossistemas industriais, há atualmente tendências no sentido de aprofundar a integração vertical e horizontal dentro da estrutura dos processos de inovação. Isso acarreta complicações de abordagem para a implementação das funções de gerenciamento. As soluções de problemas de gerenciamento e desenvolvimento em ecossistemas industriais multiníveis tornam-se particularmente relevantes. O objetivo do estudo é formular uma possível abordagem para a solução desses problemas que possa aumentar a eficiência da tomada de decisões gerenciais. O trabalho propõe a modelagem simultânea baseada em agentes e o uso de gêmeos digitais de vários níveis para simular processos econômicos. O estudo propõe um esquema conceitual de sistemas industriais multinível para uma modelagem baseada em agentes, levando em conta sua estrutura verticalmente hierárquica. O modelo proposto identifica quatro níveis (com seus próprios agentes), que diferem na natureza das tarefas a serem resolvidas, na área de responsabilidade e nos mecanismos organizacionais e econômicos usados. Propõe-se que o modelo se baseie em ferramentas econômicas e matemáticas, especialmente em métodos de modelagem por computador, criando especificamente gêmeos digitais. Os gêmeos digitais são usados para analisar as cadeias de produção, avaliar o efeito de fatores internos e externos, desenvolver alternativas e selecionar as soluções mais preferíveis para o surgimento de problemas de gerenciamento. Ao mesmo tempo, foi determinado que a estrutura dos gêmeos digitais deve ser multicamadas, em que cada nível subsequente incorpora gêmeos digitais desenvolvidos no nível anterior, dotados de funções implementadas em um determinado conjunto. Ficou comprovado que uma das tarefas importantes é determinar a configuração ideal da camada gerencial de gêmeos digitais do ecossistema industrial. Essa camada é responsável pela modelagem do componente organizacional e gerencial e é construída com base nas necessidades para atingir os indicadores de metas de atividade financeira e econômica. O estudo propõe e descreve o mecanismo de operação do modelo baseado em agentes, cujo desenvolvimento permite produzir estratégias de gerenciamento baseadas em ferramentas complexas de modelagem econômica e matemática, análise de cenários e previsões e modelagem numérica de gêmeos digitais.

Palavras-chave: Modelagem baseada em agentes; Ecossistema industrial; Gêmeo digital multicamada; Arquitetura digital; Complexo industrial.

1 INTRODUCTION

In modern economic conditions, modeling socio-economic processes problem is often used for management and forecasting purposes. Economic theory and practice focus today is on issues related to key industries production organization and management, with its overall efficiency increasing aim. Industrial complex changes studies, taking into account its complexity, requires tools that can adequately describe complex relationship systems.

Managing industrial ecosystems in global digitalization context requires their dynamic development from the inside, taking into account flexible adaptation possibility in the external environment. In industries' development management and forecasting problems, there are many characteristic parameters. It is quite obvious that in order to configure these parameters and select their reasonable combination, it would be useful to have a tool for preliminary

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assessment of both the consequences changes in external environment and various regulatory measures implementation effects.

Agent-based modeling (ABM) can be one such tool. In general, we can say that ABM is a simulation modeling method that studies decentralized agents behavior and how it determines entire system as a whole. Agent-based modeling can help clarify internal processes details and dynamics, which can then be incorporated into scenario models to predict various future scenarios and make decisions based on this information.

The research hypothesis is based on an assumption that industrial ecosystems agent-based modeling of various hierarchical levels helps to improve the strategic and operational management in industrial infrastructure facilities creation. At the same time, in addition to classical modeling using industrial agents (stakeholders), the work proposes to use digital twins concept. For various organizational and management tasks, it is expected to use digital twins with functionality variety.

Through the combined use of agent-based models and digital twins, it is possible to deeply analyze ecosystems' growth, stability and sustainability various scenarios impact. At the same time, ecosystems themselves are proposed to be considered from multi-level approach perspective, which helps to understand how different levels and actors interact to support and develop the industry as a whole.

In this regard, this study proposes a rationale for agent-based approach use in combination with multi-layer digital twins concept aiming to solve management and prediction problems. This problem has several key aspects: research object dynamism, stakeholders diversity, uncertainty in planning, different scenarios adoption. Thus, study's goal is to develop a conceptual methodology for industrial ecosystems agent-based modeling using digital twins.

2 LITERATURE REVIEW

One of the most productive approaches to creating tools for complex systems dynamics prediction is simulation modeling, agent-based modeling specifically (Rand & Stummer, 2021; Scheller et al., 2019).

Agent-based modeling focuses on individual agents' behavior (often represented as agents or agent systems), their interactions, and over time evolution. It goes beyond traditional concepts based on analytical approaches by modeling micro-level systems, taking into account heterogeneous market participants and their interactions. These stakeholders are represented as agents with individual preferences, knowledge and behavior. Agent-based modeling can help clarify the details and internal processes dynamics, which can then be incorporated into scenario models to predict various future scenarios and make decisions based on this information.

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Initially, the agent-based modeling methodology was formed by Thomas Schelling (1971) while studying society segregation. In modeling industrial development, this approach is reflected in studies by Romero, Ruiz and others (Fraccascia et al., 2020; Romero & Ruiz, 2014). Special mention should be made regarding agent-based models formed by researchers at Russian Academy of Sciences Central Economic Mathematical Institute, in which control systems functioning and high-tech and industrial clusters management were studied (Abramov, 2019; Makarov et al., 2017; Ramzaev et al., 2017). The article (Akberdina & Shorikov, 2022) presents a hierarchical agent-oriented model of industrial complex management; Korovin (2020) proposes regional industrial complex digital transformation architecture agent-oriented model.

A digital twin (DT) is classically defined as a virtual copy of a real product, system, being, communities and even cities that is constantly updated with data from its physical counterpart as well as the environment (Jiang et. al., 2021). According to Gartner Research (Gartner, 2019), an organization's digital twins are expected to become critical as digital business systems increasingly rely on human and machine intelligence integration. A digital twin provides valuable data to create industrial ecosystem scenarios that can be used in models to accurately represent assets or systems current state. In addition, the digital twin can be used to conduct simulations and test various scenarios without affecting the real object. This allows to assess how changes may affect the object and its operation. Digital twins usage benefits research amount continues to grow. Currently production and supply chains digital twins exist in many large international companies and have detail varying levels. Technological advances have enabled digital twins in manufacturing early stages moving from being machine-centric to fully digitally representing manufacturing processes. Digital twins provide a holistic view and allow to use various strategies for business scenarios implementation in a virtual environment without affecting physical production and order flow (Green, 2023; Hoffman et al., 2023; Parmar et al., 2020; Soori et al., 2023).

Digital twin technologies are successfully used in various industries, including product design, production, forecasting, management, etc. (Asad et al., 2023; Lu et al., 2020; Makarov et al., 2019; Melesse et al., 2021; Yi et al., 2021).

A number of studies indicate the need to combine digital twin technology and artificial intelligence to achieve synergistic effects (Dirnfeld et al., 2022; Minerva et al., 2023; Mo et al., 2022). In order to achieve the greatest efficiency, agent-based models are used that describe autonomous agents interaction in order to identify their behavior and predict the results obtained from such interaction (Campos et al., 2020; Huckert et al., 2023). The effectiveness of using agent-based models in conjunction with digital twin technologies has been proven in practice using the example of supply chain modeling (Orozco-Romero et al., 2020).

Some studies consider an engineering platform for industrial import substitution as an

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example of using digital twins for decision-making in industry. Unlike the physical element of the equipment, where there are objective restrictions to achieving 100% independence, the potential for import substitution of the digital element has almost no limitations and is recognized as a development priority for reasons of production and information security in compliance with the requirements of the best available technologies (Mikhailidi et al., 2023).

Thus, business processes transfer to a digital environment and its modeling, taking into account various agents participation and their risks can stimulate industrial ecosystems development. Digital twin and agent-based modeling can be used together to better understand and manage complex systems, providing interactions more accurate and detailed modeling between agents and objects in a digital environment.

3 METHODOLOGY

3.1 Technology platforms and industrial ecosystems

In the following work, the terms “technology platform” and “industrial ecosystem” will appear. Therefore, before presenting the research methodology, it is advisable to introduce the reader to the author’s vision of these concepts.

In our view, the technology platform and industrial ecosystem are two key elements of modern industrial infrastructure and economic activity that interact with each other and contribute to industries innovations development and growth.

In this study, industrial ecosystems are understood as economic systems at different levels. (R&D department, factories, enterprises, corporations/holdings, industries) participating in industrial technology platforms. In a multi-level setting, the term "industrial ecosystem" represents an organizational structure in which industrial system components and elements are organized into hierarchical levels. This hierarchical structure usually makes it easier to manage and control various aspects and operations in an industrial ecosystem. Thus, a multi-level industrial ecosystem is a concept that describes a complex and interconnected network of stakeholders operating within an industrial sector. This ecosystem includes different levels of participants and interactions, enabling collaboration, competition and innovation throughout the hierarchy. A technology platform is understood as a business model of special type and mechanism for innovation process organizing, based on a system inherent in a specific, relatively stable network that unites representatives of the state, business, science and education around scientific and technological development common vision and approaches to new innovative technologies development. Based on the technology platform, consumer value creation interconnected processes in economy’s various sectors are developing (Chursin et al., 2022). Products created often include components produced by different organizations, which requires all participants in the process to integrate into a single information environment.

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Typically these are corporate information systems, which, depending on the tasks being solved, are platform solutions such as CAD, CAE, MES, PLM, etc.

A technology platform can serve as a basis for innovation and industrial ecosystems development. It provides tools and resources to create new products and services, as well as to optimize business processes within the ecosystem. In turn, industrial ecosystems act as technology platforms agents, using them to create innovative products and services.

Taking into account that within technology platform framework, several industrial ecosystems are involved in creating a product, each of which has its own resources set, business processes, management, strategizing and budgeting features, while it has its own risks and logistics processes, and there are risks and logistics common to the entire organizational structure. There is a need to manage these risks and logistics flows, as well as general management functions implementation by business process technology platform central participant – its owner. One of the possible approaches to solving this problem could be agent-based modeling, understanding that industrial ecosystems - participants in a technology platform are agents with their own resources, technologies, risks (which may entail higher-level risks for the entire technology platform) , as well as information systems use.

3.2 Industrial ecosystems agent-based modeling conceptual diagram

Figure 1 presents agent-based multi-level industrial system conceptual diagram. This diagram illustrates agent-based industrial ecosystem management. The model reflects management vertical hierarchy in industrial ecosystem and represents structural elements interaction divided into two groups: objects and subjects. The model identifies four levels, differing in the nature of the tasks being solved, responsibility area, organizational and economic mechanisms used. The digital twin in this case acts as an immanent structure that carries out data accumulation, scenario analysis and forecasting. Each of the four levels in the presented diagram includes its own agents set.

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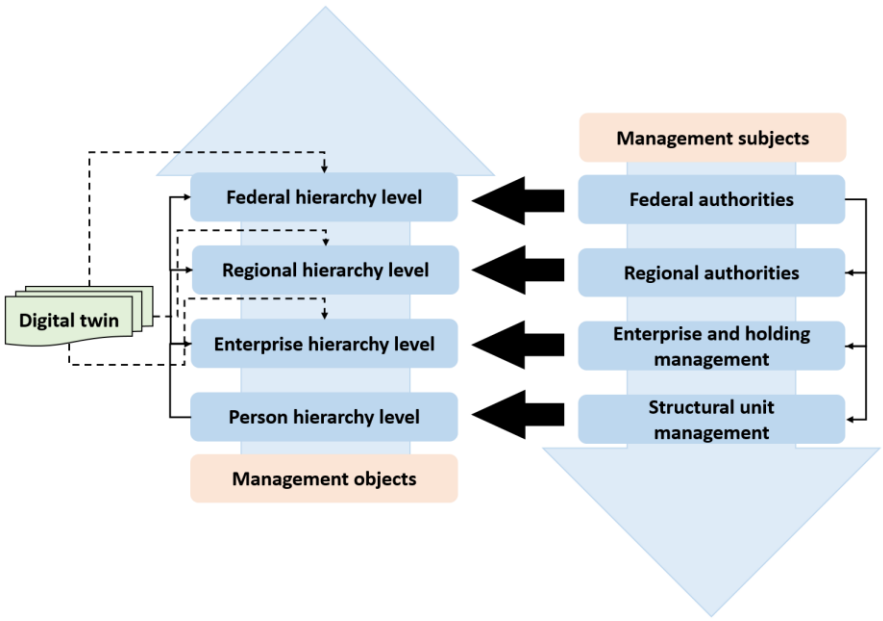

Figure 1. Multi-level industrial systems agent-based modeling conceptual diagram

According to presented model hierarchy, lower-level management object is human capital, subordinate to enterprise departments corresponding heads. Further, enterprises, regions and countries management levels are considered. The arrows in the figure reflect control diffusion process. Strategic decisions made by government are passed down the chain and further to responsible executives. Management results, in turn, expressed by industrial products and developed technologies, is vertically integrated into management objects structure, which is also presented in Figure 1.

Figure 2 presents a decision support mechanism using agent-based modeling technologies.

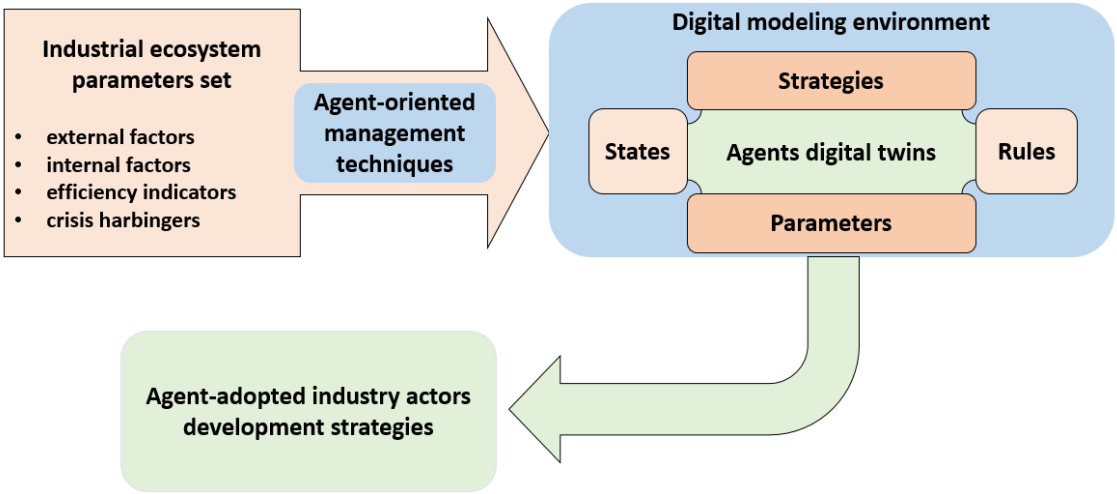

Figure 2. Decision support mechanism using agent-based modeling technologies

The proposed structure satisfies system analysis basic principles: the management problem is decomposed, external and internal factors are systematized, and management subject

influence assessed. It is based on economic and mathematical modeling tools, in particular, computer modeling methods – digital twins creation. Using computer modeling, production chains are analyzed, the effects of internal and external factors are assessed, alternatives are developed, and the most preferable solutions to emerging management problems are selected.

Complex production systems agent-based modeling involves participating agents characteristics systematizing. Thus, it is advisable to consider the classification by types, parameters, states and agents control strategies (Korovin, 2020). Classification basis is agents' differentiation according to industrial ecosystem hierarchy and functioning parameters. The key parameters seem to us to be indicators of internal and external business processes, the level of digitalization and dependence on imports, which is reflected in the figure below (Figure 3).

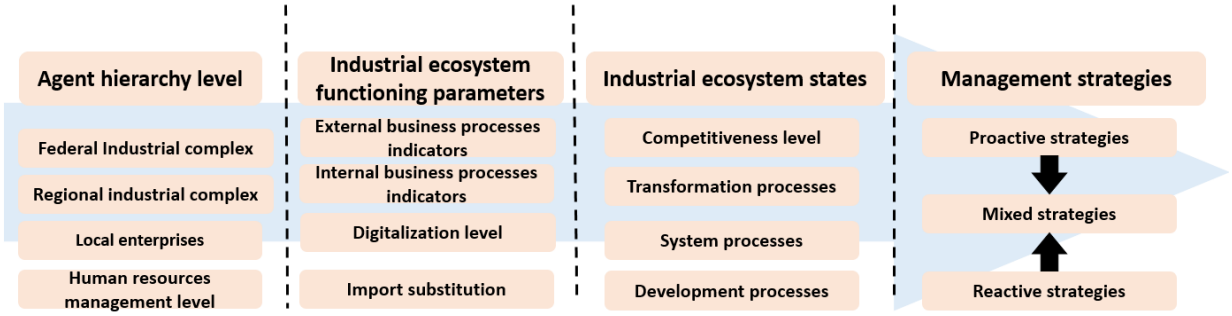

Figure 3. Main characteristics of model agents

In accordance with the accepted classification and taking into account hierarchical levels and monitored characteristics, it is proposed to identify industrial ecosystem several states that correspond to its functioning processes. Thus, it is proposed to implement monitoring mechanisms in relation to competitiveness, industrial development processes and digital transformation dynamics. Monitoring result is effective management strategies development, including reactive, proactive and mixed approaches.

3.3 Digital twin multilayer structure

Speaking of the model above, key addition to traditional agent-based modeling is digital twins' usage. In this case digital twins' structure should be multi-layered. Each subsequent level incorporates digital twins developed at the previous one (Figure 4).

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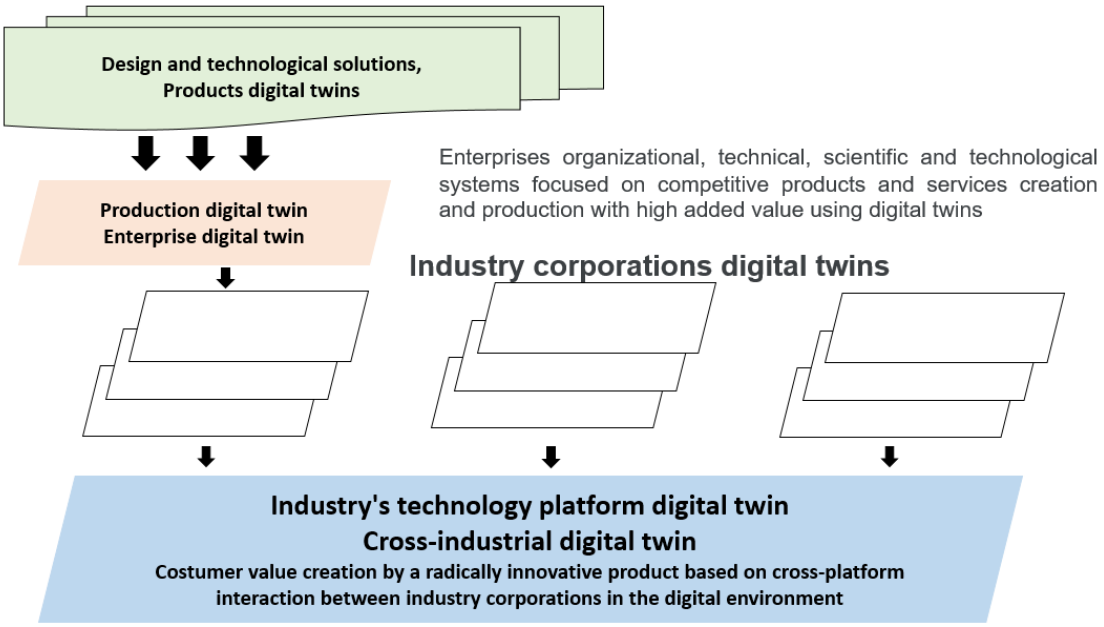

Figure 4. Relationship structure between different levels digital twins

In order to build such a multilayer structure, appropriate application software solutions are required. Currently, there are plenty of standard digital solutions suppliers on the market for certain processes modeling. For example, Mavim provides software that enables companies to build digital operating models that are challenged by changes in technology, competition, and consumer behavior to quickly respond to rapidly changing environments. The Ortelius DTO digital platform also supports organizations' business processes digital transformation.

Most effective digital model choice for production processes functioning and involved resources combinations is a digital twin. Digital twins at industry's different hierarchical levels allow to solve various management problems. Table 1 shows their systematization.

Table 1. Digital twin hierarchy

Hierarchy level	Digital twin	Purpose
Product	Physical product virtual replica or model created using digital technology and data	Productivity increase, costs reduction and product reliability increase, providing more effective product life cycle management
Production	Complex virtual prototype for all types production resources	Production operations monitoring, analysis, optimization and management, efficiency improvement, production quality and reliability growth
Company	Entire enterprise virtual view and model, including its business processes, operations, structure, resources and assets using digital technologies and data	Business process modeling, data integration, analytics and forecasting, resource and asset management, monitoring and optimization, digital strategy, scenario and risk modeling.
Industry	Real sector industry replica using data and digital transformation technologies.	Data collection, modeling, data analysis, allowing to optimize production processes, testing strategies and industry development scenarios. New products development and testing, risk and safety management
National industrial complex	Virtual model and manageable digital infrastructure representing all sectors and key	Data integration, various economic development scenarios simulation, resource and efficiency management, forecasting and strategic planning,

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	elements of the country's industrial economy	industrial infrastructure safety and sustainability level assessment, risk analysis, innovations stimulating, real-time monitoring and control

Thus, industrial ecosystem digital twin can be defined as a digitalization object that most accurately describes real cause-and-effect relationships between stakeholders. This is a concept that creates entire ecosystem virtual representation, which includes not only specific industrial enterprises, but also their interactions, connections, resources and processes.

3.4 Industrial ecosystem digital architecture

Studying industry 4.0 activity model building approaches experience made it possible to form industrial ecosystem architecture model, shown in Figure 5.

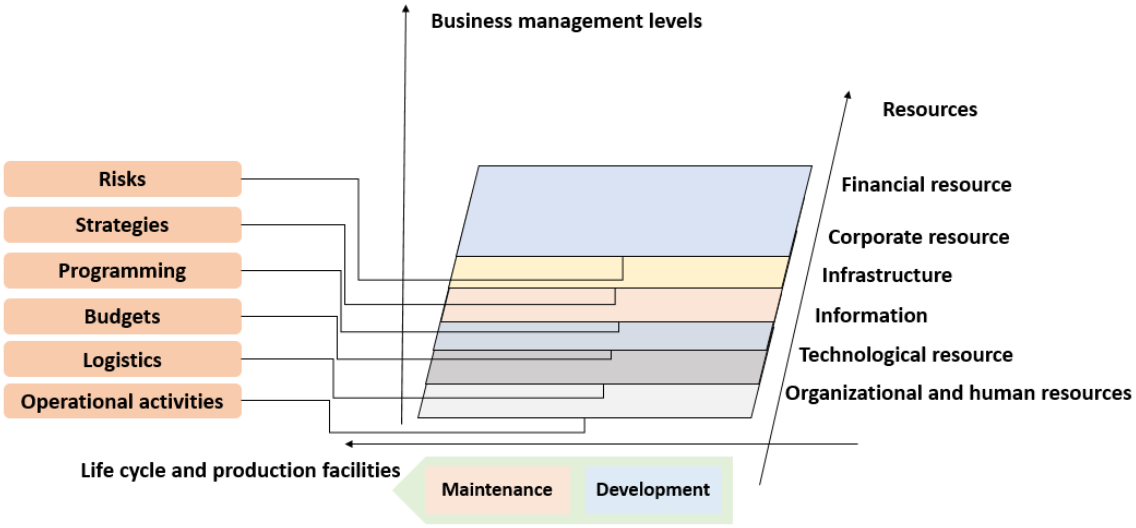

Figure 5. Industrial ecosystem architecture model

The industrial ecosystem architecture model is displayed in three measuring dimensions:

Dimension 1: Business process management layers (levels);

Dimension 2: Product life cycle stages;

Dimension 3: Resources used.

Architecture's first fundamental parameter is business processes that require regulation and digitization based on standard operating procedures, subject to security. In the architecture model they are represented by six levels (layers):

- risk management system;
- development strategy management over a period of 5-10 years;
- activity program management over a period of 3-5 years;
- budgeting management in the period 1-3 years;

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– logistics management according to the established supply deadlines;

– operational activities management “here and now”.

The second important parameter of the technology platform agent architecture is product life cycle description and product’s mathematical and computer model significant dependence on one or another production type. At the same time, it is possible to formulate principles for organization’s digital format transition. Among them are:

1. Technical policy and ideology meaning components unification, that forms an approach to organizing production according to the strategy “components are awaiting order on the shelf”;

2. Methodological policy - standardization as a way to ensure built-in product quality through both ‘static’ products and production processes digital models formation and “in static” and their digital twins “in dynamics”;

3. Digital twins intellectual policy - generated databases, solutions libraries in key design and manufacturing areas.

Architecture’s third parameter is a resources set (both tangible and intangible) that require management. In conditions of interaction between agents during products with new characteristics creation, resources and their combinations set will be determined taking into account agent’s involvement degree in certain business processes modeled in the digital twin.

Thus, industrial ecosystem digital twin is products and production digital twin higher level integration. It is designed to coordinate the most effective way to solve problems, both production and organizational. At the same time, creating a higher level digital twin is impossible without lower-level digital twins formation. The formation process occurs by “layering” on the functions already implemented in products and production digital twins, which make it possible to implement the product lifecycle, production and technological processes in a digital format, allowing to model organizational and managerial processes occurring in the organization. At the same time, the following tasks will be solved on digital twins basis:

– forecasting development taking into account dynamically changing internal and external environment factors;

– increasing production amount by optimizing it and business processes efficiency growth;

– industry’s operational organizational and management problem-solving.

3.5 Organizational and management functions digital twin

Industrial ecosystem digital twin configuration, which is responsible for modeling the organizational and managerial component, is based on the need to achieve financial and economic activity target indicators, reflected, among other things, in strategies and programs developed by almost all organizations, on the one hand, and on the other, – based on those

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processes, actions and factors that influence these indicators achievement. Moreover, factors can arise both in the short and long term and be natural or chaotic.

During processes monitoring and modeling, factors and actions can most effectively be carried out using organization's digital twin that implements at least the following functions key set presented in Figure 6, while allowing actions' impact assessment on modeled agent financial and economic activity.

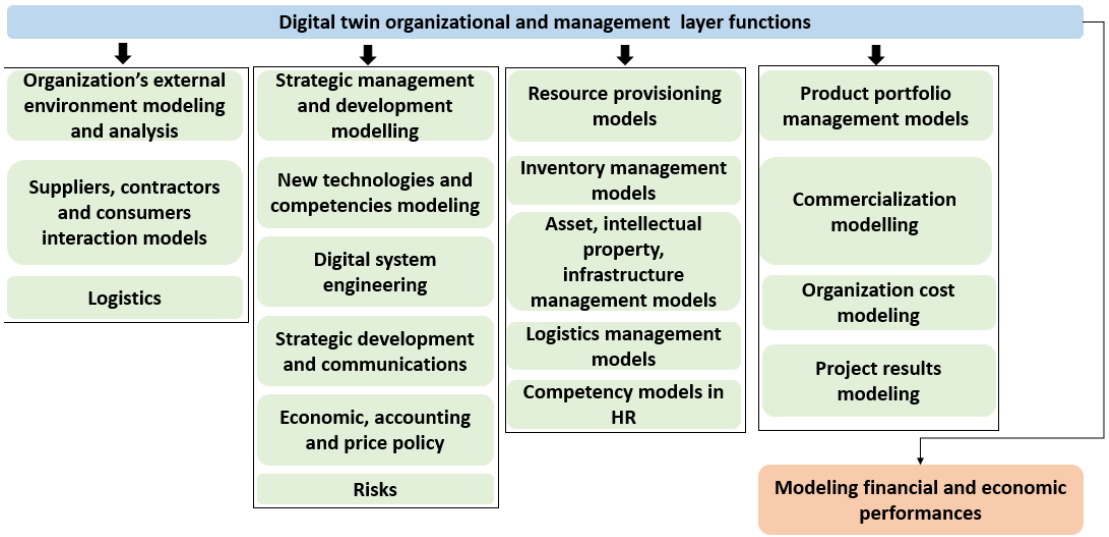

Figure 6. Industrial ecosystem digital twin organizational and management layer functions

The proposed digital twin is a solution that most accurately describes the real cause-and-effect relationships between productions, economic, financial and organizational indicators. Digital twin's goal is the presence in the information environment of a dynamic programmable model, which, based on real-time and retrospective data analysis forms a knowledge base for decision making.

Digital twin concept can be developed and extended to complex objects such as departments, business units, entire enterprises, industries and even national industrial systems to support specific financial or other processes during decision making, providing opportunities for digital business models building, organization's financial and economic activities effectiveness management, business operations analytics and processes and scenarios modeling for managing projects and organization as a whole.

4 DISCUSSION AND RESULTS

Agent-based modeling in industrial ecosystems management problems is justified by several factors:

1. Actors heterogeneity and adaptability.

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2. Emergent phenomena studies.

3. Dynamics and time aspects.

4. Experiments and scenario analysis.

5. Uncertainty and risks.

6 Strategic planning support.

To take these factors into account, we have developed an agent-based modeling algorithm based on the author's methodology. The presented factors justify the need to develop new and update existing approaches to heterogeneous industrial ecosystems management. For example, actors' heterogeneity and adaptability factor creates digital technologies implementation need for data processing and analysis. Experiments and scenario analysis, along with the need to account uncertainty and risk, are pushing industrial ecosystems digital twins use, while support for strategic planning requires digital simulation tools for production systems (Figure 7).

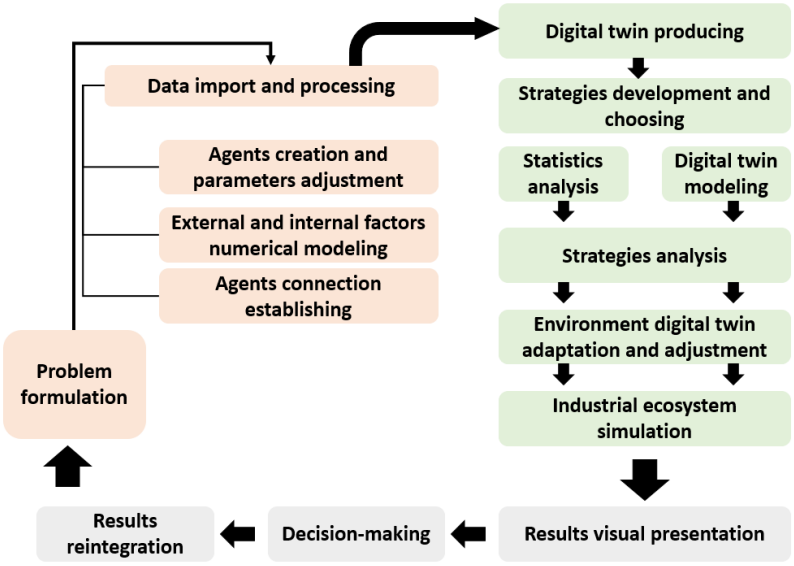

Figure 7. Agent-based model working mechanism

In a larger scale, the modeling algorithm for an agent-based model can be represented in the form of three stages:

1) Initial setup: creating agents, if necessary, determining their location, setting parameters from an available database, as well as configuring the environment and determining external influences.

2) Simulation: running an interaction process in which agents choose their strategies, interact with each other, exchange resources and collect statistical data.

3) Obtaining results: loading statistical data, analyzing aggregated indicators, assessing system's macro parameters, processing information and visualizing it.

Formalizing behavior rules that agents apply is the most difficult and critical aspect of the

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model creation process. By developing the architecture of this model, it is possible to establish general relationships that determine agents' actions. Each time the model runs, enterprises choose their own strategies, taking into account their internal conditions, the environment, regional governance influence, and possibly other agents actions within the enterprise. In addition, strategy choice for introducing digital solutions depends on company leaders' personal characteristics.

Presented model further development is in management strategies, based on a economic and mathematical modeling complex, scenario and forecast analysis and numerical modeling using digital twins. Integration of modern tools for processing and analyzing information into management mechanisms contributes to complex tasks implementation.

5 CONCLUSION

Modern world requires new approaches to industrial ecosystems development, within which most high-tech products stages creation are implemented. At the same time, new approaches must take into account the risks associated with a significant increase in requirements for product creation timing, quality and costs. Such conditions imply an increase in the pace of project implementation with the obligatory condition that final products quality does not deteriorate. Classical approaches can no longer ensure compliance with modern requirements for product creation.

The article proposes and describes an industrial ecosystem architecture model based on a multi-level digital twins (product, production, enterprise, industry, national industrial complex). To implement the management function based on digital twins, it is proposed to consider agent-based models that allow to take into account various internal and external factors.

This approach based on agent-based modeling allows, in particular, at the enterprise level to implement systems engineering principles, allowing to build not only functionally basic product modules, but also to form an enterprise management system platform for model-based systems engineering (MBSE) and simulate trajectory changes in finance and economics, choosing the most profitable way to implement strategic plans while minimizing risks.

For example, this approach assumes that in a single engineering field, a digital design bureau, all design work required according to the technical specifications and in accordance with government standards is carried out using a variety of CAD, CAM, PLM system modules, such as: system design, circuit design, printed circuit board design, modules, devices, units, etc. At the same time, agent-based modeling is carried out. Having comprehensive modeling and digital twins modeling-based refinement ultimately eliminates erroneous design decisions and applies corrective actions early in the product lifecycle, significantly reducing the cost of an error.

At the production stage, digital twins make it possible to achieve technological operations

maximum automation and proven, qualified technical processes use. To do this, technical process parameters maximum amount is automated. If any deviations are diagnosed, based predictive agent-based modeling, corrective measures are taken. Ensuring guaranteed product quality through qualified technological processes, automatic control and production automation allows to keep deviations risks at minimum level and radically reduce manual control operations number at technical control departments' level. At the same time, to ensure quality control and prevent errors, technical vision systems can be used to supply the information necessary for modeling.

Multi-level digital twin and agent-based models introduction another benefit is in simulation-based calculations results recognition as an evidentiary tool for confirming products suitability, i.e. their qualifications. It is necessary to understand that for such modeling practical usage, methods for verifying software, computer models, calculation models, mathematical apparatus, as well as a knowledge base for statistical data significant amount regarding are required.

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