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APPROACH TO ORGANIZING DISTRIBUTED PRODUCTION OF UNMANNED AERIAL VEHICLES USING DIGITAL TWIN AND MULTI-AGENT SYSTEMS TECHNOLOGIES

*The research focuses on methods and software tools for decision support for the organization of distributed production of unmanned aerial vehicles (UAVs) based on digital twin and multi-agent systems technologies. The **purpose** of the work is to provide a critical review of existing approaches to the organization of distributed production of UAVs, as complex technical objects, and to substantiate an approach to building a multi-agent decision support system for the synthesis of a rational production structure based on digital twins of participants in production cooperation. The tasks include: classifying unmanned aerial vehicles according to the main features that determine their production specifics; analysing modern scientific publications in the field of distributed production informatization, multi-agent systems, digital twins and intelligent decision support; identifying the limitations of existing solutions; and proposing an approach to the organization of distributed production of UAVs using digital twins in the form of intelligent agents. The applied **methods** are based on system and classification analysis, generalization of modern scientific approaches to the organization of production, decision-making theory, the concept of multi-agent systems, digital twin technologies, production logistics and artificial intelligence. The following **results** were obtained: UAVs were classified by mass, purpose and level of autonomy, which made it possible to determine the specifics of their production and life cycle management. An analysis of scientific publications was performed, which showed the active development of areas related to the use of multi-agent systems, digital twins and artificial intelligence to address complex tasks in UAV life cycle management. It was established, in particular, that the works of recent years consider the issues of cooperative UAV production, the use of deep learning algorithms for decision-making in dynamic environments and the integration of digital twins into relevant production systems. At the same time, a number of limitations on the implementation of existing solutions were identified: insufficient formalization of business processes between production participants, weak integration of digital twins into production logistics, and the lack of self-organization mechanisms. An approach to solving the problem of effective organization of distributed UAV production is proposed. The architecture of a multi-agent decision support system for distributed UAV production is developed, which includes modules for coordination, self-organization, and the evaluation of the effectiveness of production configuration options, considering the initial risk tolerance indicator. **Conclusions**. The scientific novelty of the results obtained is as follows: an approach to solving the problem of effective organization of distributed UAV production is proposed, which, unlike existing ones, is based on the representation of production participants as digital twins in the form of intelligent agents, this enables the generation of multiple options and the subsequent selection of the most rational configuration for organizing distributed UAV production in terms of business process efficiency and the reduction of production risks. The research results create a basis for further integration of multi-agent technologies into real-world manufacturing platforms and the expansion of their application to other types of complex machinery.*

***Keywords:** unmanned aerial vehicles (UAVs); distributed manufacturing; multi-agent systems; digital twins; decision support; business processes; risk tolerance; self-organization; production logistics; artificial intelligence.*

1. Introduction

The modern development of industry is characterized by an active transition from centralized to distributed forms of production organization [1], within which the creation of complex technical products is ensured by the cooperation of several independent participants [2, 3]. This approach is due to the increasing complexity of technical systems, the need to involve highly specialized production competencies [4], as well as the desire to increase the flexibility, adaptability and economic efficiency of production processes [5, 6]. One of the most illustrative examples of such products are unmanned aerial vehicles (UAVs), which combine aerodynamic, structural, electronic, software and communication components.

Unmanned aerial vehicles belong to the class of complex technical objects, which are characterized by high scientific intensity, multi-component structure and critical dependence on the coordination of actions of all participants in the production process. Their creation requires cooperation of enterprises specializing in the design, manufacture of components and assemblies, integration of subsystems, software, testing and maintenance [7, 8]. As a result, the process of organizing distributed UAV production goes beyond the classical technologies of creating production and logistics schemes and requires the use of modern approaches to information support for decision-making regarding the organization of this class of objects.

1.1. Motivation

The need to study the problem of decision support for the organization of distributed UAV production is due to a number of factors. First, in such systems, the number of alternatives for configuring production links between cooperation participants increases significantly. For each option for organizing production, it is necessary to take into account the production capabilities of enterprises, resource constraints, technological compatibility, logistical characteristics, interaction risks and the potential effectiveness of the final configuration [9]. Taken together, this forms a complex task that cannot be effectively solved without specialized software tools.

Secondly, traditional information systems for production purposes, in particular ERP, MES, SCM and others, are mainly focused on supporting the functioning of already defined organizational structures and are poorly adapted to the tasks of forming new configurations of distributed production. They do not provide a sufficient level of flexibility, poorly take into account the behavioral characteristics of participants, do not allow modeling interaction processes in a dynamic environment and do not provide effective means of supporting multi-criteria choice [10].

An additional motivation is the active development of digital twins, multi-agent systems and artificial intelligence methods, which create the prerequisites for building new classes of software decision support systems [11]. The use of digital twins allows for the creation of formalized virtual representations of potential production participants, and multi-agent technologies allow for the modeling of their interaction, coordination, and self-organization. It is the combination of these approaches that is promising for the development of software tools capable of supporting the choice of a rational option for organizing distributed UAV production.

1.2. Publication Analysis

Analysis of modern research shows that in recent years the problem of digitalization of production systems has been considered mainly within the concepts of smart manufacturing, digital twin, cyber-physical production systems and distributed decision-making. At the same time, most of the works either focus on the technological level of digital modeling or on the tasks of optimizing individual production processes, without providing a holistic approach to supporting decision-making regarding the configuration of distributed production of complex technical objects, in particular UAVs.

In the work of Lu et al. [12], the digital twin is considered as the basis of smart manufacturing and a reference model of digital twin-driven manufacturing is proposed. The authors systematize the areas of application of digital twins, in particular, monitoring, forecasting, optimization and service support, and also outline key research problems. The authors of the article have generalized the conceptual foundations of digital twins in industry, however, it does not consider the tasks of organizing interaction between independent production participants, which is critical for distributed UAV production.

The article by Leng et al. [13], contains a review of approaches to designing smart manufacturing systems based on digital twins is conducted. The authors show that digital twins can be used not only to display production facilities, but also to support the design and reconfiguration processes of systems. At the same time, the main emphasis in this work is on the engineering design of production systems, and not on representing cooperation participants as autonomous entities capable of interaction, negotiation and local decision-making.

The work of Wang et al. [14] is devoted to the approach to building a digital twin in smart manufacturing based on the combination of the digital twin model and the UNISON framework. The authors try to move from general concepts to a more applied model suitable for manufacturing systems. The article focuses on modeling the components and operating rules of a digital twin, however, the digital twin is treated mainly as a model of a manufacturing system, and not as an intellectual representative of a separate entity of distributed production.

Wilhelm et al. [15] review interaction-based approaches to digital twins in smart manufacturing. The authors focus on how a digital twin can support human-machine interaction in cyber-physical systems, presenting the digital twin not only as a model of equipment, but as an active element of the digital environment. However, the work is focused on the HMI aspect and does not address the problem of modeling business processes and the behavior of manufacturing partners in a distributed environment.

In the publication of Onaji et al. [16], a conceptual framework for digital twin in manufacturing is proposed with application case studies. The authors demonstrate that the digital twin is an effective tool for data integration, visualization support, and analytics with the

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transition from abstract concept to application cases. However, the work does not contain a formalized approach to building digital twins of independent manufacturing entities and does not consider the configuration of the cooperative structure as a decision support task.

In the article Ivanov and Dolgui [17] introduced the concept of a digital supply chain twin as a supply chain for risk management and increasing supply chain resilience. The authors show that a digital twin can be used as a tool for modeling network states in real time and stress testing possible violations. In this paper, digital twins are considered not from the level of a single object, but from the level of a network system. At the same time, the emphasis is on supply chain resilience, and not on the software architecture of a multi-agent decision support system for configuring production. Further development of this logic is presented in the work of Ivanov [18], where the concept of intelligent digital twin (iDT) for stress-testing, resilience and viability supply chains is proposed. The author forms a generalized framework for using a digital twin as an intelligent DSS, combining digital mapping, analytics, AI components and decision-making rules. The article shows the possibility of transitioning from a passive digital model to an active intelligent system. At the same time, the work primarily considers the supply chain context and does not propose a model of a digital twin of an individual production participant in the form of a software agent.

The publication by Pulikottil et al. [19] is devoted to a thorough review of the options for applying agent-based technologies in smart manufacturing. The authors performed a SWOT analysis of agent-based solutions and confirmed the feasibility of their use for decentralized control of production systems. The practical value of this work lies in the fact that it demonstrates the relevance of MAS for reconfigurable and distributed manufacturing. However, the review nature of the publication does not provide a specific model for combining the agent approach with digital twins of cooperation participants.

The work of Li et al. [20] proposes a multi-agent digital twin-enabled decision support system for supplier management. The authors combine digital twins, agent interaction, and mechanisms for assessing the stability and sustainability of supplier management processes. In this paper, the authors demonstrate the practical feasibility of integrating digital twins and MAS in a DSS context. At the same time, its subject area is focused on supplier management, rather than on the formation of a distributed production configuration of UAVs as a self-organizing logistics system.

In the article Freese and Ludwig [21] proposed a conceptual framework for supply chain digital twins. The authors emphasize the need to move from individual use cases to a holistic architecture of digital twins of network systems. The authors of the article summarized the requirements for digital twins of supply chains and emphasized the importance of interorganizational integration. However, the article did not disclose the software-agent mechanism for building such twins and did not introduce an indicator for evaluating the efficiency of the production system configuration.

Gálvez del Postigo Gallego et al. [22] review decision support solutions within manufacturing digital twins. The authors show that digital twins are increasingly integrated with decision support services, which opens up the possibility of moving from monitoring to management support. However, the article is of a review nature and does not propose a specific multi-agent method for building a decision support system for distributed manufacturing.

Thus, the analysis of modern publications shows that the scientific community already has significant results in the areas of digital twins, multi-agent systems, resilience analysis and DSS for production and logistics environments. However, the task of integrating these approaches into a single software system, where participants in distributed UAV production would be represented as digital twins-agents, and the choice of the configuration of the production system would be carried out on the basis of a formalized assessment of its initial risk tolerance, remains open. It is this gap that determines the scientific feasibility of the approach proposed in the article.

1.3. State of the art

The problem of organizing distributed UAV production lies in the need to form a rational configuration of potential participants in production cooperation in conditions of multi-criteria, uncertainty and dynamism of the external environment. In practice, this means the need to make decisions on the selection of the composition of participants, the distribution of functions between them, the definition of logistical connections, and the assessment of the compatibility and stability of the future production system.

Existing approaches to decision support in production systems, as a rule, do not provide an integrated representation of cooperation participants, do not take into account their autonomy and behavioral characteristics, and do not allow evaluating production organization options as holistic self-organized systems. As a result, a scientific and applied problem arises of developing models, methods, and software tools that would provide decision support for organizing distributed UAV production based on a formalized representation of participants and mechanisms of their interaction.

1.4. Objectives and tasks

The purpose of the article is to analyze the possibilities of applying existing methods and software tools to support decision-making regarding the organization of distributed production of UAVs as complex technical objects, as well as to substantiate the approach to building a multi-agent system based on digital twins of participants in production cooperation. This approach enables the development and evaluation of distributed UAV production configuration options based on initial risk tolerance, thereby improving business process efficiency and reducing production risks.

To achieve the goal, within the framework of this publication it is necessary to solve the following **tasks**:

1. Analyze the features of distributed production of UAVs as complex technical objects.
2. To classify unmanned aerial vehicles, taking into account the characteristics that affect the organization of their production.
3. Develop an approach to solving the problem based on the use of digital twins of production participants in the form of intelligent agents and a multi-agent decision support system.

2. Classification of UAVs

Unmanned aerial vehicles are complex technical systems that can be classified according to various characteristics, the main ones being scale, functional purpose, and design features. Table 1 presents a classification of UAVs, which allows us to systematize their characteristics and take into account the specifics of production when organizing distributed production systems.

From the point of view of production organization, unmanned aerial vehicles are characterized by a modular structure, which involves division into functional subsystems, including the airframe, power plant, control system, navigation system and payload.

Table 1

Classification of unmanned aerial vehicles

No.	Classification sign	UAV type	Characteristic	Production features
1	By mass and scale	Micro-UAV	Weight up to 2 kg, short flight range	High serial production, use of standard components
2		Mini-UAV	Weight 2–20 kg, medium range	Combining standard and specialized components
3		Tactical	Weight 20–150 kg, significant flight duration	High specialization of production, cooperation of enterprises
4		Operational-strategic	Weight over 150 kg, long range and autonomy	Complex integration of subsystems, multi-level cooperation
5	By appointment	Reconnaissance	Observation, monitoring	Sensor systems integration
6		Shock (combat)	Hitting targets	High requirements for reliability and safety
7		Cargo	Cargo delivery	Reinforced structures, logistical integration
8		Civilian	Agriculture, geodesy, inspections	Adaptability to operating conditions
9	By type of construction	Aircraft type	Long range and speed	Complex aerodynamic design
10		Multicopter	Vertical takeoff and landing	Simplicity of production, electronic complexity
11		Hybrid	Combination of airplane and helicopter types	High integration complexity
12	By level of autonomy	Managed	Operator management	Simplified management system
13		Semi-autonomous	Partial automation	Integration of navigation algorithms
14		Autonomous	Fully automatic control	Use of artificial intelligence systems

This approach allows for the involvement of different manufacturers in the creation of individual components, which forms the basis for distributed production [23, 24].

At the same time, the growing complexity of UAVs, increasing requirements for their reliability and functionality, as well as the need to integrate disparate technologies, necessitate the use of specialized methods and software to support decision-making in organizing production.

Distributed production, in turn, is a complex organizational and technical system consisting of a set of interacting participants who perform various functions within a single production process [25]. Such systems are characterized by:

- decentralized management structure;
- the presence of a multitude of legally and functionally independent entities;
- complex topology of interactions;
- dynamic configurations;
- high level of uncertainty.

Informatization of such systems involves the creation of software tools capable of providing decision support in complex conditions of multi-criteria and uncertainty. At the same time, traditional approaches to production automation are focused mainly on centralized control systems, which limits their effectiveness in distributed environments.

3. Approach to organizing distributed production of unmanned aerial vehicles

Proposed approach to organizing distributed production of UAVs based on the phased implementation of a multi-agent decision support system that uses digital twins of production participants. Each stage has a clearly defined goal, methodological basis, and software implementation.

Stage 1. Formalization of business processes of production participants. At this stage, an analysis of typical functions, resources and interactions of enterprises that may be involved in UAV production is carried out. Business processes are formalized in the form of structured models that reflect the logic of production activities.

Stage 2. Building a digital twin of a typical potential production participant, in the form of an intelligent agent. Formalized business process models are transformed into software structures — digital twins, implemented as intelligent agents. Each agent has the ability to autonomously make decisions, communicate, and adapt to changes in the environment.

Stage 3. Architectural modeling of a multi-agent system. Based on a set of digital twins, a multi-agent system is formed that models the logistics structure of distributed production. The system architecture includes coordination, self-organization, and efficiency assessment modules (Fig. 1).

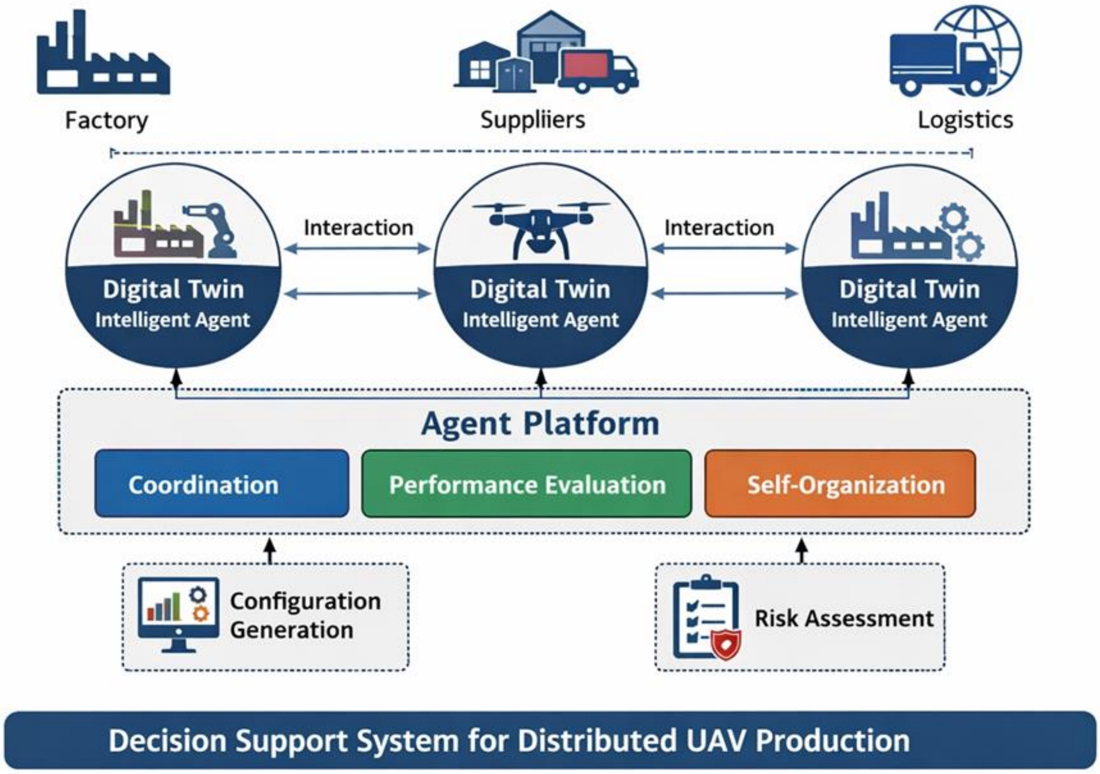

Fig. 1. Architecture diagram of a multi-agent system for distributed UAV production

Digital twins of production participants (intelligent agents) model enterprises, resources and business processes. The agent platform provides coordination, efficiency assessment and self-organization of the system. The configuration module generates production organization options. The risk assessment module determines the initial risk tolerance and helps to choose the optimal option. The decision support system integrates all components, ensuring effective management of distributed UAV production.

Stage 4. Formation of production configurations. Agents interact with each other, generating variants of production system configurations. Resource availability, logistical connections, time constraints and production capacities are taken into account.

Stage 5. Evaluating the effectiveness of distributed generation configuration options. A method for evaluating the effectiveness of configuration options based on the initial risk tolerance index is proposed. This index reflects the system's ability to withstand external risks in the process of self-organization.

Stage 6. Software implementation of the decision support system. A prototype of a software system is being developed that implements the described models and algorithms. The system provides automated generation of configurations, their evaluation, and selection of the optimal option.

This approach allows for the formalization of enterprise business processes, their integration into a multi-agent system, and provide decision-making support in a dynamic logistics environment.

3. Results and Discussion

According to the results of the analysis, it was found that modern software tools for production informatization, in particular ERP, MES, SCM and PLM systems, provide automation of individual functional processes, but are not focused on supporting decision-making regarding the formation of a rational configuration of distributed production of unmanned aerial vehicles. It is shown that for such tasks, it is not enough to automate resource accounting or monitor the performance of production operations, since it is also necessary to take into account the interaction of independent participants, the multi-criteria nature of choice and the influence of uncertainty.

A review of current publications has determined that multi-agent systems are a promising tool for modeling distributed production environments, as they provide the ability to represent individual participants as autonomous software entities capable of interacting, coordinating, and agreeing on decisions. However, it has been found that in most existing studies, agents are presented in a simplified form, without a sufficiently complete reflection of real business processes and production capabilities of enterprises.

It is also established that the concept of digital twins creates new opportunities for formalizing the characteristics of production facilities and processes. However, in existing works, digital twins are mainly used for monitoring, simulation or optimization of individual technical operations and are not sufficiently used as a basis for supporting decision-making on the organization of cooperative production. This is especially important for UAVs, which as complex technical facilities are characterized by a modular structure, a high level of technological specialization and the need for cooperation of a significant number of participants.

The results of the analysis indicate that individual multi-criteria evaluation methods can be used to select options for distributed production configurations, but they do not provide comprehensive consideration of the self-organization of the logistics system and the risks associated with it. In this regard, it is advisable to introduce an additional evaluation criterion related to the initial risk tolerance of the production configuration.

Thus, the analysis confirms the feasibility of the proposed approach, which is based on the use of digital twins of production participants in the form of intelligent agents, their integration into a multi-agent system and the application of the initial risk tolerance indicator to evaluate alternatives. This approach allows combining the means of formalizing participants, mechanisms of their interaction and decision-making support tools within a single software environment that meets the needs of organizing distributed UAV production

4. Conclusions

The article considers the current scientific and applied problem of decision support for the organization of distributed production of unmanned aerial vehicles as complex technical systems. It is shown that the modern conditions for the creation of UAVs are characterized by a high level of cooperation, a multivariate configuration of production interaction, the dynamism of the external environment and the need to coordinate decisions between independent participants in production. This necessitates the use of specialized software tools capable of providing intellectual support for the processes of analysis, selection and evaluation of options for organizing distributed production.

The classification of unmanned aerial vehicles allowed us to generalize their main types and functional features, as well as to show that UAVs should be considered as typical objects of distributed production. It was established that the complexity of their design, modular structure, high requirements for subsystem integration and significant technological specialization of production

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participants necessitate the use of new approaches to organizing interaction between production entities.

Analysis of modern publications in recent years has shown that research in the field of digital twins, multi-agent systems, decision support systems and production logistics is actively developing in the scientific literature. At the same time, it was found that existing approaches, as a rule, are focused on the automation of individual processes or on local optimization problems and do not provide a comprehensive solution to the problem of forming a rational variant of the organization of distributed UAV production. The main disadvantages of existing solutions are limited integration of models of production participants, insufficient adaptability to environmental changes, weak formalization of business processes and the lack of effective mechanisms for evaluating production system configurations.

Based on the analysis, the feasibility of using an approach based on the representation of distributed production participants in the form of digital twins, implemented as intelligent software agents, is substantiated. It is shown that the combination of such agents into a multi-agent system creates the prerequisites for building a software environment for decision support that can take into account complex interactions between participants, mechanisms of self-organization of the logistics system, and the dynamic nature of the production environment.

The results of the research create a theoretical basis for further development of models, methods and software tools for decision support in the organization of distributed production of UAVs. The main areas of further research should include: development of a formal model of a digital twin of a typical participant in distributed production; creation of a method for forming and configuring production organization options based on agent interaction; development of a method for evaluating the effectiveness of configurations taking into account the initial risk tolerance indicator; as well as algorithmic and software implementation of a decision support system with subsequent experimental verification of its effectiveness.

Contributions of authors: conceptualization, methodology – **Mariia Danova;** formulation of research goals and objectives **– Mariia Danova;** conducting research on the current state **- Victor Shalnyev;** development of an approach to organizing distributed production of UAV – **Victor Shalnyev;** development of multi-agent system architecture for distributed UAV production **– Victor Shalnyev;** interpretation of results **– Mariia Danova, Victor Shalnyev.**

Conflict of Interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, author ship or otherwise, that could affect the research and its results presented in this paper.

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This study was conducted without financial support.

Data Availability

The work has associated data in the data repository.

Use of Artificial Intelligence

The authors confirm that they did not use artificial intelligence methods while creating the presented work.

All the authors have read and agreed to the published version of this manuscript.

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ПІДХІД ДО ОРГАНІЗАЦІЇ РОЗПОДІЛЕНОГО ВИРОБНИЦТВА БЕЗПІЛОТНИХ ЛІТАЛЬНИХ АПАРАТІВ, З ВИКОРИСТАННЯМ ТЕХНОЛОГІЙ ЦИФРОВИХ ДВІЙНИКІВ ТА БАГАТОАГЕНТНИХ СИСТЕМ

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Предметом дослідження є методи та програмні засоби підтримки прийняття рішень щодо організації розподіленого виробництва безпілотних літальних апаратів (БПЛА) на основі технологій цифрових двійників і багатоагентних систем. **Метою** роботи є критичний огляд існуючих підходів до організації розподіленого виробництва БПЛА, як складних технічних об’єктів, а також обґрунтування підходу до побудови багатоагентної системи підтримки прийняття рішень щодо синтезу раціональної виробничої структури на основі цифрових двійників учасників виробничої кооперації. **Завдання**: виконати класифікацію БПЛА за основними ознаками, що визначають специфіку їх виробництва; провести аналіз сучасних наукових публікацій у сфері інформатизації розподіленого виробництва, багатоагентних систем, цифрових двійників та інтелектуальної підтримки прийняття рішень; виявити обмеження існуючих рішень; запропонувати підхід до організації розподіленого виробництва БПЛА з використанням цифрових двійників у вигляді інтелектуальних агентів. Застосовані **методи** базуються на системному аналізі, класифікації, цифрових двійниках, теорії прийняття рішень та штучного інтелекту. Було отримано такі **результати**. Проведено класифікацію БПЛА за масою, призначенням та рівнем автономності. Виконано аналіз наукових публікацій, який показав активний розвиток напрямів, пов’язаних із застосуванням багатоагентних систем, цифрових двійників та штучного інтелекту для вирішення комплексу завдань з управління життєвим циклом БПЛА. Розроблено архітектуру багатоагентної системи підтримки прийняття рішень щодо розподіленого виробництва БПЛА. **Висновки**. Наукова новизна отриманих результатів полягає в наступному: запропоновано підхід до вирішення проблеми ефективної організації розподіленого виробництва БПЛА, якій на відміні від існуючих базується на представленні учасників виробництва як цифрових двійників у вигляді інтелектуальних агентів, що надає змогу обрати серед них найбільш раціональний варіант організації розподіленого виробництва БПЛА.

Ключові слова: безпілотні літальні апарати (БПЛА); розподілене виробництво; багатоагентні системи; цифрові двійники; підтримка прийняття рішень; бізнес-процеси; ризикостійкість; самоорганізація; виробнича логістика; штучний інтелект.

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