CONTROL PROCESSES

The object of the study is the project-production activity of project-oriented enterprises in the fields of mechanical engineering, aircraft construction, shipbuilding, instrumentation, and metallurgy.

The problem addressed was the informational integration and synchronization of project management processes, implemented by a specific project-oriented enterprise, with the management of its production processes using digital twins. The solution to this problem is aimed at improving the efficiency of project-production management by utilizing digital twins of projects and production in the planning process.

The influence of trends on the development of digital technologies was analysed. The need to consider both project and operational activities of enterprises in mechanical engineering, aircraft construction, shipbuilding, instrumentation, and metallurgy as a single project-production activity was identified. It was shown that this approach can be successful when processes and changes in project-production activity can be modelled, forming a rational plan for product release and project execution. The use of digital twins for objects and processes in project-production activities was proposed.

The aim and objectives of the study were formulated, focusing on the creation of a concept for planning project-production activities using digital twins for objects and processes in both project and operational activities.

The concept defines the structure of the digital environment for project-oriented production, a model of the interpenetration of project and production planning processes, an aggregated critical path method, and simulation modelling for planning project-production activities using digital twins. It was shown that to model project-production activities, models and methods for managing the interaction between the operational and project processes of the company must be applied. It was proposed to use the scientific and practical tools of information interaction theory to manage this interaction.

The results of applying the concept in project-oriented companies were demonstrated. The use of tools created based on the proposed concept allowed a reduction in project execution time by 10–15 % and a decrease in production costs by 5–10 % due to effective planning of project-production processes

Keywords: digital project management, digital twins, information technology in project management, digital transformation

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DEVELOPMENT OF A CONCEPT OF COMBINED PROJECT-PRODUCTION ACTIVITIES PLANNING USING DIGITAL TWINS

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1. Introduction

The activities of most companies in the fields of mechanical engineering, aircraft construction, shipbuilding, instrumentation, and metallurgy are project-oriented. Modern requirements for managing their activities demand the use of new approaches, concepts, methods, models, and tools that meet these demands. From the perspective of project orientation, it is impossible to overlook the current trends in project management, which involve the creation and merging of methodologies, tailored to the company's conditions, with digital project management into a unified system. This combination allows, on the one hand, the adaptation of project management methodologies to the enterprise's conditions, and on the other hand, the minimization of human involvement in project management, thereby enhancing the effectiveness and objectivity of decision-making. Along this path, the major trends of Industry 4.0 and 5.0, particularly those related to the digital transformation of all aspects of human activity, must be considered.

Thus, the digital transformation of society, the economy, and companies within the framework of the fourth and fifth industrial revolutions necessitates changes and the development of management tools in the mentioned fields – mechanical engineering, aircraft construction, shipbuilding, instrumentation, and metallurgy. A distinctive feature of these fields is that the material resources for projects (such as parts, components, and assemblies) are often produced by the enterprises themselves. Essentially, the activities of such enterprises are not just project-oriented; they are project-production-oriented: production-oriented in terms of manufacturing resources for projects, and project-oriented in terms of using these resources. This further complicates the task of finding optimal solutions for the enterprise's operations, both in project and production contexts. It is very difficult to solve this task without accurately predicting the consequences of decisions related to the planning of production and project activities. And it is impossible to achieve such forecasting without precise modelling of all the processes within the enterprise.

Of course, there have been previous attempts to implement planning processes for such enterprises by creating informational and mathematical production models, followed by their simulation. However, these models did not account for the main feature of combining project and production processes – rapidly changing, dynamic operating conditions. The project portfolio in these fields is not static; it is replenished with new projects throughout the year, client requirements change for existing projects, project documentation is updated, and the schedules for product manufacturing and project implementation are adjusted. Additionally, production capacities and orders from external clients for the enterprise's products are not constant. Therefore, these process models must continuously synchronize with the actual processes, which is precisely the strength of digital twins. A digital twin is a virtual representation of a physical object, process, or system that is continuously updated (synchronized) based on real-time data and used to forecast and manage the real object, process, or system. According to ISO 23247, a digital twin is a digital model of a specific physical object, process, or its life cycle, ensuring convergence between the physical and virtual states with an appropriate synchronization speed.

Thus, the digital twin paradigm creates new, broader possibilities for planning project-production processes in the fields of mechanical engineering, aircraft construction, shipbuilding, instrumentation, and metallurgy. Therefore, research dedicated to the development of tools for combined project-production planning using digital twins is highly relevant.

2. Literature review and problem statement

The current realities of industrial production development present important strategic challenges, centred on the ability to quickly introduce, adaptively plan, and produce new products. The adaptability of project-production planning is one of the key success factors for Industry 4.0 (5.0). For this reason, significant increases in the efficiency of project-oriented companies can only be achieved through:

a) digital transformation and information integration of product lifecycle data,

b) the application of modern project management methodologies,

c) the use of digital twins technologies and tools.

According to a study [7], the digital twin (DT) market, valued at $6.9 billion USD in 2022, is expected to grow significantly to $73.5 billion USD by 2027. This rapid growth of 60.6 % over five years is driven by substantial economic benefits, improved efficiency, and new functional capabilities for industrial enterprises.

From a management perspective, a digital twin helps to understand not only how a specific production system operates but also how it will function in the future. This enables timely responses to changes and the making of optimal managerial decisions. A digital twin can also be a digital copy of a project, allowing the reproduction of project processes for effective management. In this case, digital project twins enable the prediction of how the management system or process will work using real-time data and simulations. Artificial intelligence, simulation methods, and predictive models can be employed to improve outcomes. The use of digital twins in project management enhances strategic decision-making, prevents costly resource losses, and allows planning to consider the project's status in all its dimensions, utilizing advanced analytical, predictive, and monitoring capabilities.

To address the problem of information integration and synchronization of project management processes with production management via digital twins, the use of digital twins in project and enterprise management was analysed. Significant progress in this direction has been made by the European scientific community, which has initiated programs such as IoTwins [8], Change2Twin [9], and DigitBrain [10]. These programs aim to promote the rapid and cost-effective implementation of digital twins among industrial enterprises.

The DigitBrain [10] project aims to unlock the innovative potential of manufacturers through Digital Twins. Change2Twin [9] supports small and medium-sized manufacturing businesses in the process of digitalization.

IoTwins [8], a project supported by the European Union under the Horizon 2020 program, successfully concluded in 2022. It uses big data to develop smarter and more efficient approaches to predictive maintenance, optimization, and planning of production operations in industrial manufacturing. The project is aimed at supporting the digital transition of industrial enterprises by providing them with methodologies and tools that leverage the potential of the digital twin paradigm [11, 12].

However, while these projects address both operational and project activities of industrial enterprises, they do not utilize combined (integrated) planning to improve production efficiency.

The authors of the paper [13] proposed a solution for optimizing industrial production schedules using a global digital twin. They developed a decision-making structure for dynamic planning of production systems and created mathematical and computer models that integrate local and global digital twins, using optimization algorithms and autonomous decision-making alongside real-time data analysis. However, despite the inclusion of elements from project management theory, the joint use of production and project activities for planning purposes is not considered in this work.

In [14, 15], the use of digital twin integration to enhance production management efficiency is discussed as a core component for smart planning and project management within the context of Industry 4.0. Optimization algorithms for planning and process management modelling based on digital twins and integration with various systems through IoT and cyber-physical systems are proposed. The limitation, however, is the absence of modelling for project-production processes in these studies.

The authors of [16] describe how digital twin services can improve production planning and enhance the accuracy of production processes by introducing digital twin as a service for smart manufacturing. Project solutions for creating a model integrating digital twins with necessary service platforms, using machine learning algorithms to optimize production processes, are proposed. The use of the digital twin service is considered from the perspective of project management, particularly in managing projects without solving planning tasks.

The work [17] presents the development of a strategy for modelling and using digital twins in process planning to improve the accuracy and efficiency of planning and production management processes. A method for real-time synchronization using digital twins for assembly schedule planning is described in [18]. However, these works lack information on the informational implementation of the presented modelling. Methods and technologies for using artificial intelligence and digital twins for planning and managing the production of complex products in assembly shops are proposed in [19]. Forecasting and data analysis, as well as integration with ERP systems to improve production process management, were implemented. The limitation is that the work does not address the application of models and methods for project management planning.

The research results on dynamic process planning using digital twins and reinforcement learning, presented in [20], are of scientific and practical interest. The authors used machine learning algorithms and simulations for adaptive planning and optimization of production processes. However, these works address process planning without information integration with project activities.

At the same time, it should be noted that the issue of joint planning of project and production activities has been discussed in scientific studies. For example, the work [11] is dedicated to adjusting traditional approaches to operational management for production activity planning, including project support. The works [12, 13] focus on creating subsystems for project management support, including the provision of products from production activities. These subsystems, while maintaining a project-oriented focus, implement resource management functions for projects and combine project management functions with the management of project resource provisioning. However, these works do not address the coordination of operational and project processes in the fields of mechanical engineering, aircraft manufacturing, instrumentation, and metallurgy, nor do they utilize the potentially attractive functional capabilities of digital twins.

Overall, an analysis of papers published in scientific metric databases such as Scopus and Web of Science over the past five years has shown a significant increase in publications focused on the development of tools for creating digital twins. At the same time, there is a noticeable lag in the scientific and methodological aspects of using the functional capabilities of digital twins to enhance the efficiency of project-oriented production activities in industrial enterprises.

It can be stated that, as of today, there are no available tools for integrating the operational and project activities of project-oriented companies under the conditions of their digital transformation. This unresolved aspect of the problem presents an objective need for the development of new approaches to managing project-oriented companies in the context of digital transformation.

One possible solution to this problem lies in the creation of digital twins for production and projects, with the simulation of all operational and project processes in a digital environment. Such twins would facilitate the identification of optimal solutions regarding production volumes and timelines for projects, as well as the scheduling of product usage in projects. Therefore, the issue of information integration and synchronization of project management processes implemented by a specific industrial enterprise with the management of its production processes using digital twins requires further research.

3. The aim and objectives of the study

The aim of the study is to develop a concept for planning project-production activities using digital twins. This will enable increased management efficiency for enterprises in the machine-building, aircraft-building, instrument-making, shipbuilding, and metallurgical industries.

To achieve the aim, the following objectives were set:

– to develop an approach to combined planning of project and production activities for project-oriented enterprises;

– to propose a structure for the digital twin environment of projects and operational production;

– to build a model for synchronizing digital twins in the process of combined planning of project and production activities;

– to develop a method for combined planning of project-production activities for companies using digital twins of projects and productions.

4. The study materials and methods

The object of the study is the project-production activities of project-oriented enterprises in the machine-building, aircraft-building, shipbuilding, instrument-making, and metallurgical industries.

In this concept of planning project-production activities under the conditions of digital transformation of project-oriented enterprises, only the operational features of companies in the machine-building, aircraft-building, instrument-making, shipbuilding, and metallurgical industries were considered. Accordingly, the modelling of production aimed at supplying products for projects of these productions was carried out within processes typical for enterprises of the specified profiles.

The assumption of the work is that companies implementing the proposed concept have specialists capable of executing the digital transformation of their company, as well as applying tools for both project planning and operational activity planning. Additionally, it is assumed that all information about machines, equipment, resources, and production processes is available in the company's digital environment, or that an information technology system containing this data is implemented at the enterprise.

Based on this, the research hypothesis is that effective planning of project-production processes is only possible through the creation of digital twins of project and production processes.

These twins are then used in a unified digital environment for combined planning, enabling the rational coordination of tasks to produce items for projects and the execution of project tasks.

Experimental research was conducted in functioning companies in the machine-building, aircraft-building, and metallurgical sectors, allowing practical verification of the proposed concept's adequacy and the effectiveness of planning methods based on the use of digital twins for projects and operational production. The proposed concept was applied to the planning of project-production processes at an aircraft manufacturing company and a company producing complex geological equipment [21, 22].

5. Results of the research on planning processes for project-production activities using digital twins

5. 1. Approach to combined planning of project and production activities in project-oriented enterprises

By combined planning of project and production processes, we will understand an iterative method of coordinating within a company the processes of manufacturing products for projects and project tasks execution. Through this method, a rational option for project-production activities is selected (Fig. 1).

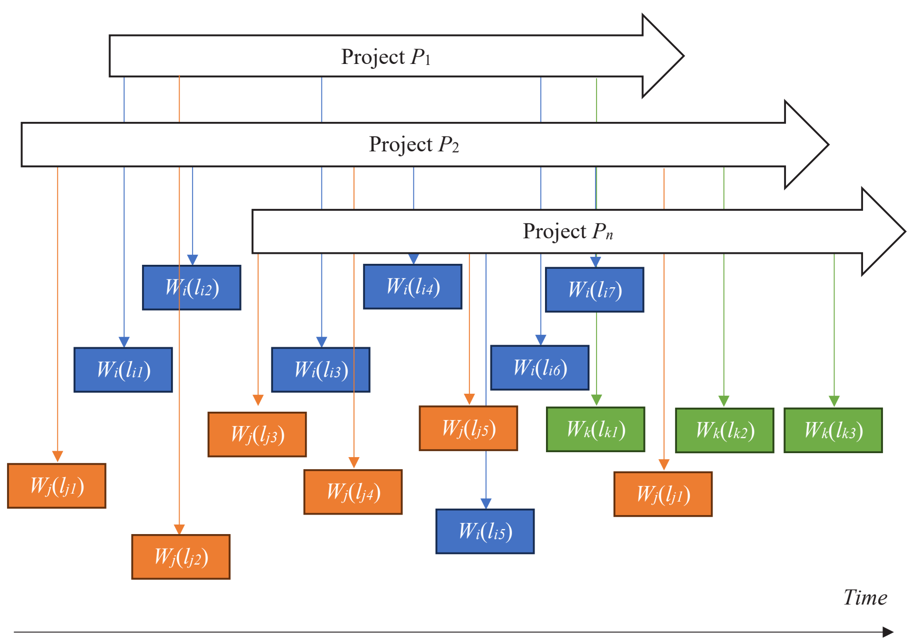

Fig. 1. Schematic chart of the enterprise's product demand for projects: $W_i(l_{is})$ – product W_i, project demand – l_{is} units

In various industries where project-production activities are implemented, such as in machine-building, aircraft-building, shipbuilding, instrument-making, and metallurgical industries, the task of combined planning of operational and project processes at the enterprise management level arises. Solving this task without the company's digital transformation and modelling various options for organizing the production of items for projects alongside the options for executing project tasks in the digital environment is practically impossible. Therefore, the strategic goal of every project-oriented company is digital transformation, which would ensure the creation of a qualitatively new management system for the company's project-production activities as an element of digital project management [23–26]. The creation of digital management tools through the development of a new approach to managing the project-production activities of enterprises is essential.

Considering the dynamic nature of both production and project processes [27], there is a need to digitalize all management processes, creating information models of production and projects in the digital environment. The concept of digital twins is the most suitable for this purpose, being a modern approach to developing digital technologies for modelling, forecasting, and managing various processes and systems [8–12, 21, 22]. Given the complexity of industries such as machine-building, aircraft-building, shipbuilding, instrument-making, and metallurgical, the creation of digital twins of projects and production in the digital environment becomes necessary, where their interaction will represent a model for the development of real-world production and projects.

Within the framework of the concept of planning project-production activities using digital twins of projects and operational production, the following tasks of managing project-production activities are outlined:

1. Creation of a digital twin environment for operational production and projects.

2. Synchronization of digital twins when new projects emerge, changes occur in the equipment used by the enterprise, or adjustments are made to the labour resources supporting the company's project-production activities.

3. Planning, acquisition, and distribution of labour and material resources for projects and production activities.

4. Synchronization of project-production activity plans: planning projects considering the production activity plan; planning production activities considering project plans.

5. Selection of a rational option for implementing the company's production activities and executing projects.

6. Generation of the selected version of the combined plan for the company's project-production activities.

7. Coordination and approval of the combined plan.

Of course, management approaches based on informational models have been known for a long time. However, digital twins offer a new quality that stems from their definition – they are continuously updated objects in a virtual (digital) environment [7, 8, 12]. This quality is linked to the constant synchronization of the twin with the real object or process. When a solution to a given task is found in the digital twin environment, it can be applied to real objects and processes. Specifically, in solving the task of planning project-production processes, it is possible to model these processes in the digital twin environment and find the optimal (rational) solution. This solution can then be used to synchronize the operation of the enterprise's equipment and the labour resources involved in the projects. The digital twin environment allows for the exploration of various combinations of synchronizing project-operational processes and selecting the option that meets both the interests of the project clients and the enterprise itself, which produces items for these projects.

Therefore, the tools within the digital twin environment for combined planning of a company's project-production activities should include means for project planning, production planning, and coordination of the project plan with the production plan. While tools for project planning (e.g., Microsoft Project, Oracle Primavera, etc.) and production planning (ERP systems) are used successfully on their own, tools for harmonizing project and operational plans are practically non-existent. Their implementation is impossible without modelling different options for product output and project task execution.

To achieve the formulated goals and develop an effective technology for planning project-production activities in a company undergoing digital transformation as part of digital project management, the proposed approach will include:

1. The structure of the digital twin environment.

2. Synchronization of objects and processes involved in product manufacturing for projects and the execution of project tasks with the digital twins of project-production activities.

3. Combined planning of project and operational processes by creating a variety of implementation options and selecting the rational one that forms the basis of the company's project-production activity plan.

Let's examine the components of this approach in more detail.

5. 2. Structure of the digital twin environment for projects and operational production

The concept of a "Digital Twin" has become a global brand, widely used in various scientific and applied fields. However, this widespread use is happening without a well-established conceptual framework and a sufficient methodological foundation based on relevant ISO standards. Formally, all components of a digital twin can be classified as follows:

1. Elemental components:

1. 1. Physical (can be a product, process, task, or their lifecycle).

1. 2. Digital (virtual component).

1. 3. Information flow between the physical and digital asset, synchronized in real time.

2. Imperative components:

2. 1. Internet of Things (IoT) devices, automated systems with feedback, and other tools to collect information from various subcomponents of the physical asset and peripheral devices.

2. 2. Information data collected in real-time from different components and software, as well as data from specific cloud-based digital services.

2. 3. Methods and technologies for high-precision modelling – for predicting and implementing feedback, as well as identifying effective strategies to mitigate or eliminate errors and issues with the physical component.

Clearly, other elements can be added to this classification, such as large databases with experimental data, data security, hybrid and distributed virtual models, etc. Given this information, it is evident that the definition of a digital twin in the ISO standard does not fully reflect the current state of this important concept.

Digital twins are computer models of a physical and virtual product or process, or their lifecycle. They are synchronized in real time through their bidirectional comparison to predict their characteristics, solve problems, and ensure the required quality [28].

From this definition and the experience of conducted research, the feasibility of creating industrial digital twins becomes evident. These digital twins are virtual representations of physical industrial assets, processes, and systems. Such a twin serves as a dynamic digital counterpart of a physical asset or process in real time, allowing for monitoring, management, and optimization in a virtual environment.

In general, the function of planning is a key component of both project management and production processes. Project-production activities and their planning processes in the fields of machine-building, aircraft-building, shipbuilding, instrument-making, and metallurgy share many similarities. Project-production activity at these enterprises includes working with equipment to manufacture products for projects and utilizing these products in project operations. Therefore, the digital twin environment must encompass both digital representations of production processes and digital representations of project processes. This environment consists of two types of twins: production process twins and project process twins.

Production processes involve digital twins containing all the necessary data on equipment used to manufacture various products for projects, and beyond. Project processes refer not only to tasks where these products are used (as components for project outcomes) but also to the processes of ensuring the availability of these components (ordering, receiving from production, receiving from warehouse, administration). Additionally, the digital twin environment includes a modelling area containing the necessary project-production data for products manufactured by the enterprise itself and used in its own projects. This is schematically presented in Fig. 2.

The functioning of the digital twin environment involves determining the timing and volumes of product manufacturing for projects and distributing these products across project tasks. If we illustrate this process as shown in Fig. 1, it is necessary to determine for each arrow "when it will be realized" and the number of resources that will be allocated (Fig. 3).

Thus, the digital twin environment must reflect conditionally static and dynamic elements. Conditionally static elements refer to the informational data of production processes carried out on specific equipment for manufacturing products for projects and project tasks. The term "conditionally static" is used because any equipment deteriorates, requires adjustment, maintenance, or repairs. Dynamic elements refer to the data on the production outputs, for which the volumes and production times for each project may change.

When modelling the functioning of digital twins, it is essential to determine the optimal production volumes and timing that will best contribute to the successful execution of the projects.

In the process of planning project-production activities, it is necessary to obtain the following values: (r_{MS},τ_{MS}) – the volume and time of the product's readiness; (v_{SN}, t_{SN}) – the volume and time of the product's usage; $\left(T_N^S, T_N^F\right)$ – the start and finish time of the work. Based on the presented structure of the digital twin environment and considering the need to obtain the specified parameters, it is proposed to reflect the following characteristics of the objects and processes of project-production activities in the digital twins:

1. Digital twins of the production process for manufacturing a product on equipment. In machine-building, aircraft-building, shipbuilding, instrument-making, and metallurgical enterprises, this equipment includes various machines, mechanisms, conveyors, aging tanks, lifting and transport mechanisms, furnaces, pools, etc. The following information should be included for products:

1. 1. The duration of reconfiguration for product manufacturing.

1. 2. The time required to manufacture one unit of the product.

1. 3. The technological process of manufacturing.

1. 4. Working documentation for the product.

1. 5. Professional qualifications of labour resources needed for the production of this product.

1. 6. The volume of material and technical resources required per product unit.

1. 7. The working capacity of the equipment.

2. Digital twins of project processes (works) should contain information:

2. 1. Project priority – to allocate the products primarily to the most critical projects.

2. 2. The project network schedule and the position of the task within it.

2. 3. The volume of products used in project tasks.

2. 4. Alternatives to the planned products, such as other material and technical resources (possibly purchased).

2. 5. Additional project information required by other company departments, such as project budgets, labour resources, work documentation, etc.

3. Digital twins of products. These form the basis of the modelling environment (Fig. 2). They should contain the following information:

3. 1. Product description (including parameters necessary during the creation of the project product).

3. 2. The date the product was manufactured.

3. 3. Where the product is located (project product, warehouse, workshop).

3. 4. The cost of the product.

3. 5. Other information, including project-related expenses and production activities.

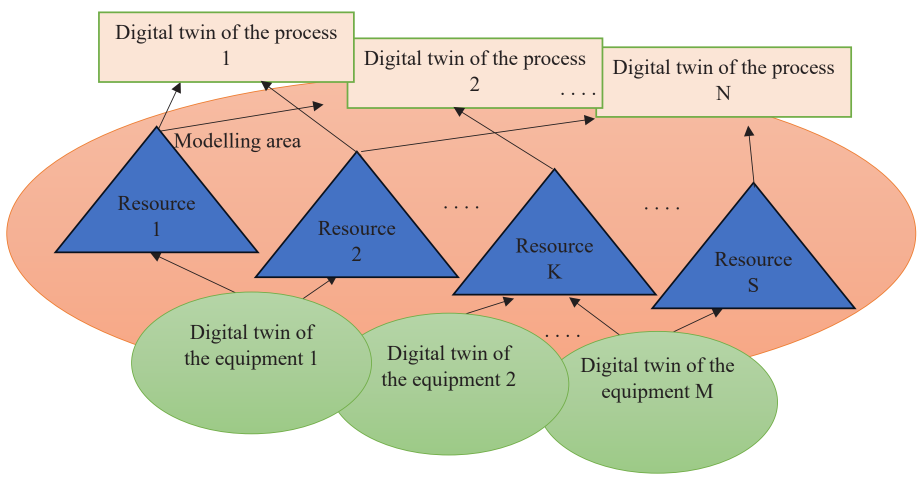

Fig. 2. Structure of the information environment of digital twins

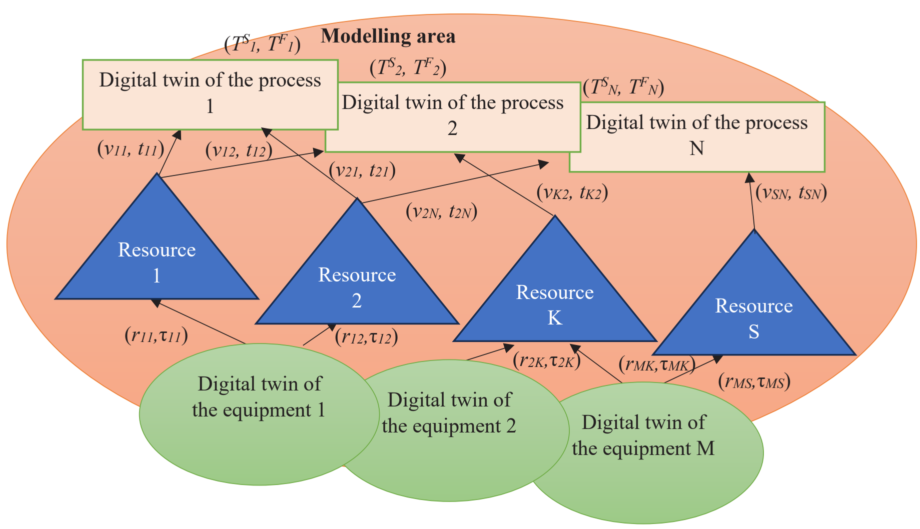

Fig. 3. Environment of digital twins specified by production volumes and time: τ_{MK} – the time of readiness of product (resource) W_K, produced on equipment Y_M; r_{MK} – the volume of product W_K, produced on equipment Y_M at time τ_{MK}; t_{SN} – the time of usage of product W_S in the task (process) P_N; v_{SN} – the volume of product W_S, used in the task (process) P_N; T_N^S – the start time of task (process) P_N; T_N^F – the finish time of task (process) P_N

Having such a structure for the digital twin environment, we can proceed to solving the main task – forming a project-production activity plan through modelling the project-production activity process at the enterprise.

5. 3. Model for synchronizing digital twins in the process of combined planning of project and production activities

Synchronization of digital twins refers to the representation of tasks and conditions of production and project activities in the digital twins. It also involves reflecting the results of modelling and planning of the enterprise's project-production activities back into real processes. Therefore, a mechanism is needed to calculate, within the environment of digital twins synchronized with real processes, the optimal order of work execution for both projects and production activities. This includes transferring the modelling results to real processes.

The input data for modelling is the information contained in the digital twins of projects and production processes. However, orders for products do not only come from projects. There can also be external clients who place orders for various products. To account for external client orders in project-production activities, we introduce the concept of a "zero-project". The zero-project reflects external client orders for products not related to project activities. In this project, each task corresponds to a separate order, and the deadlines for completing these tasks align with the product delivery dates stipulated in the company's contracts with clients. This creates a unified planning technology for both project-production activities and operational production.

In this technology, the initial determination of project task deadlines is carried out using traditional methods (such as the Critical Path Method) and tools (like Microsoft Project, Oracle Primavera). For the zero-project, deadlines are set based on contracts with the customers of company products.

The initial allocation of production tasks is determined by the volume and deadlines of orders, considering the purpose of each piece of equipment and the technological sequence of product manufacturing. The next stage is the most complex: it is necessary to synchronize the project work plan with the production schedule in such a way that the projects are completed within their respective directive deadlines. For all projects, the directive deadlines are the contractual obligations.

This model defines the conditions for the functioning of the digital twins of products and projects:

1. For projects, the initial task completion dates are not fixed, only constraints are set:

$$\forall W_{nk} \in \prod_n : T_{nk}^S > \max_{\forall W_{ni}, W_{nk} \in \Pi_n : Z_{nik}^{FS} = true} \left(T_{ni}^F + \Delta t_{nik}^{FS} \right); \quad (1)$$

$$\forall W_{nk} \in \prod_n : T_{nk}^S > \max_{\forall W_{ni}, W_{nk} \in \Pi_n : Z_{nik}^{SS} = true} \left(T_{ni}^S + \Delta t_{nik}^{SS} \right); \quad (2)$$

$$T_{nk}^F \geq T_{nk}^S + t_{nk}, \quad (3)$$

where T_{nk}^S – the earliest possible start of task W_{nk}, T_{nk}^F – the earliest possible finish of task W_{nk}, T_{ni}^F – the finish time of task W_{ni}, Δt_{nik}^{FS} – the lag/lead of the start of task W_{nk} relative to the finish of task W_{ni}, Π_n – project, W_{ni}, W_{nk} – tasks of project Π_n, Z_{nik}^{FS} – predicate that determines if there is a Finish-to-Start (FS) relationship between tasks P_{ni} and P_{nk}, Z_{nik}^{SS} – predicate that determines if there is a Start-to-Start (SS) relationship between tasks P_{ni} and P_{nk}, T_{nk}^S – the minimum constraint on the start of task W_{nk}, T_{ni}^S – the minimum constraint on the start of predecessor task W_{ni}, T_{ni}^F – the minimum constraint on the finish of predecessor task W_{ni}, Δt_{nik}^{SS} – the lag/lead of the start of task W_{nk} relative to the start of task W_{ni}, t_{nk} – duration of task W_{nk}.

2. For each type of equipment and each type of product – a schedule of product demand:

$$\forall t \forall \varphi(r_i, Y_M) = true : L(r_i, Y_M, t) = \sum_{T_{nk}^S = t} \rho(r_i, W_{nk}), \quad (4)$$

where $\varphi(r_i, Y_M)$ – predicate that determines that product r_i is being manufactured on equipment Y_m, $L(r_i, Y_M, t)$ – function that determines how many units of product r_i need to be manufactured on equipment Y_m, $\rho(r_i, W_{nk})$ – function that determines how many units of product r_i are needed to complete task W_{nk}.

(1) and (2) define the model for calculating project-production activities that will be implemented in the digital twin environment. However, for functioning of this environment, it is necessary to set the modelling parameters related to the digital twins of operational production objects – equipment available at the enterprise. From Fig. 2, a set of rules follows that defines these parameters:

$$\forall t \sum_{\tau_{jM} \leq t} w_{jM} \geq \sum_{T_{ni}^S \leq t} v_{jni}; \quad (5)$$

$$\forall t_{inj} : 0 \leq t_{jni} \leq T_{ni}^S; \quad (6)$$

$$\forall Y_M, t : \sum_{r_j} \sum_{\tau_{jM} \leq t} W_{jM} \cdot \alpha_{jM} \leq \beta_M \cdot t, \quad (7)$$

where α_{jM} – time required to produce one unit of product r_j on equipment Y_M, β_M – coefficient that determines the proportion of time when the equipment is operational, t – time point (usually a day), W_{jM} – volume of product r_j, produced on equipment Y_M at time τ_{jM}, τ_{jM} – time point when product Y_M is being manufactured on equipment r_j, v_{jni} – volume of product r_j, used in task (process) W_{ni}, τ_{jnj} – time point when product r_j is used in task (process) W_{ni}.

We can now move on to the consideration of the combined planning method for project-production activities of companies using digital twins of projects and production.

5. 4. Method of combined planning of project-production activities of companies using digital twins of projects and production

The plan calculation is based on modelling the project-production process within the digital twin environment by selecting an equipment operation scenario in which all project tasks are timely provided with the necessary components. To achieve this, a combined planning method is proposed, which involves the sequential planning of projects and component production, gradually approaching an optimal project-production activity plan. The method is based on the interaction of virtual objects – digital twins of projects and production – aimed at refining the plan. The stages of the method are as follows:

1. Calculation of the project plan.
2. Calculation of the production output plan for projects.
3. Alignment of the production output plan with project plans.
4. Evaluation of the project-production activity plan. If the plan is satisfactory, proceed to step 5.
5. Finalization of the calculation.
6. Adjustment of project plans (based on the calculation of the production output plan).

Now, the specifics of planning projects and production activities using digital twins can be considered.

5. 4. 1. Project plan calculation

For the calculation, traditional software tools such as Microsoft Project, Oracle Primavera, and others can be used. Tasks and their dependencies are selected from the digital twins of the projects. Moreover, the products necessary to create the project deliverables are included in these project tasksA traditional calculation of the project network schedule is performed. The value of $\rho(r_i, W_{nk})$ (4) is passed to the next stage. From the calculated start and end times, constraints on the start and finish of tasks $\left(T_{nk}^S, T_{nk}^F\right)$ are transmitted to the digital twins of the projects according to formulas (1)–(3). The values specified in the product supply contracts are transmitted to the digital twin of the zero-project.

5. 4. 2. Calculation of the production release plan for projects

The digital twins of projects are ordered according to the value:

$$Z_{nk} = \frac{T_{nk}^S - T_0}{\pi_n}, \tag{8}$$

where z_{nk} – the value for ordering the digital twins, T_0 – current date.

For the ordered digital twins of projects, a production release schedule is calculated according to formula (4). In this case, the digital twins of projects compete for priority in receiving their products based on the value of (8). A random number generator is used to determine the probability of a particular digital twin being prioritized, taking into account the modelling history. If in previous simulations this digital twin was chosen and the resulting plan was better than the one formed when the twin was not selected, its probability of being chosen increases. Conversely, if the plan was worse, the probability decreases. The calculation can be performed either in any ERP system or using software add-ons over project planning tools [29, 22]. The advantage of the add-on is that the selection of a digital twin based on modelling history is seamlessly integrated into this software product [28].

5. 4. 3. Alignment of the product release plan with project plans

If constraints (5)–(7) are not met, the following action is taken. If there is a production reserve for manufacturing additional products before the time when the constraints (t) are not met, a simulation is performed in the digital twin environment for producing additional products before time t, with their placement in warehouses.

If, despite this action, constraints (5)–(7) are still not met, the start times of tasks in the digital twin projects are adjusted to satisfy these constraints. The rules for adjusting the task start times are:

1. Shift tasks within the available time buffer.
2. Shift tasks according to the formula:

$$\forall W_{nk}, T_{nk}^D > T_{nk}^S : \min_{W_{nk}} \pi_n \cdot \left(T_{nk}^D - T_{nk}^S\right), \tag{9}$$

where T_{nk}^D – planned product release time for task W_{nk}, π_n – priority of project Π_n.

If the constraints are met, proceed to the next stage. If not, go to point 5. 5. 5.

5. 4. 4. Evaluation of the project-production activity plan

The criterion for evaluating the simulation results was the value equal to the product of the project priority and its execution time:

$$\sum_i \max_{\forall W_{ni} \in \Pi_n} \left(T_{ni}^F\right) \cdot \pi_n \to \min, \tag{10}$$

under the following constraints:

– project network schedules with specified task durations,

– project priorities determined by the clients.

The minimum value of expression (10) does not necessarily mean that it will be the most satisfactory for both the clients and the company management. There is a significant influence of subjective factors on the decision-making process. Therefore, the method proposes selecting the 10 best options (based on expression 10) for the company's management to review. If these plan options do not satisfy the company management, the simulation continues, starting from point 5. 5. 5. If they do satisfy, the simulation is concluded.

5. 4. 5. Adjustment of project plans (to align with the product release plan)

Digital twins of projects are considered for changes in task durations and execution order, project priority adjustments, substitution of scarce products with available ones, and the shift from manufacturing material and technical resources for project tasks to purchasing them. Afterward, using software tools, project network schedules are recalculated.

Proceed to point 5. 4. 3.

5. 5. Method verification

The distinctive feature of this method is the constant synchronization of digital twins with real production and project implementation progress. Therefore, the simulation is ongoing, with adjustments to the project-production activity plan within the given time horizon. Experience has shown that the optimal time horizon is one week.

The proposed concept has undergone practical testing during the creation of project management systems in various project-oriented companies [27, 29, 30] – "CARBON INVEST" LLC (Ukraine), PAT "TUTKOVSKY" (Ukraine), "AVK SCAETON" LLC (Ukraine). Based on this concept, information technologies were developed and implemented in these companies, including a digital database of production and project objects and the software-information add-on NadPlan. The software tools of this add-on implemented the method of combined planning of project-production activities using digital twins and the model of their synchronization. The essence of the implementation was to use the proposed concept to develop the enterprise's activity plan. This plan included both the project component (construction of mobile communication base stations, aircraft assembly, manufacturing of geological equipment) and the operational component (production of components for these projects' products). These components included: for mobile communication base stations – cabinets for equipment, electrical equipment, and towers; for aircraft manufacturing and geological equipment production – parts, assemblies, and units of finished products. The project component of the companies' activities in these areas involved assembling finished products from the produced and purchased components.

Experimental studies of these tools were conducted using the simulation modelling method during the process of selecting options for implementing the enterprise's project-production activities. In this virtual experiment, the rational allocation of products across the enterprise's equipment was determined. After obtaining a map of the product allocation across the equipment, practical development of project-production activity plans for enterprises was carried out using the developed tools. The plans for project-production activities developed in this way fully corresponded to the capabilities of producing components for project products, allowed for consistent equipment utilization, and eliminated idle time during project execution.

Thanks to better information support for the planning process of project-production activities based on the use of the digital twin environment, the costs of obtaining and using information were reduced, the quality of information improved, and data duplication was eliminated. Most importantly, it was possible to integrate the processes of project management and production through the creation of a unified project-production activity plan for companies. This allowed for a reduction in project execution time by 10–15 % and a reduction in production costs by 5–10 % due to precise calculation and planning of the required product output.

The results obtained (reduced project execution time and cost reduction) undeniably demonstrate the effectiveness of the developed concept for combined planning of project-production activities in the mentioned companies. Moreover, this proves the potential of applying the developed concept to other companies in the fields of machine-building, aircraft-building, instrument-making, shipbuilding, and metallurgy.

6. Discussion of the results of developing a concept for combined planning of project-production activities using digital twins

The concept is based on a new approach to the combined planning of project and production activities in project-oriented enterprises, the logic of which is shown in Fig. 1. This new approach to project-production activity planning, based on the use of digital twins, enabled the development of a new structure for the digital environment of the enterprise and the creation of a model and method for planning the project-production activities of the enterprise.

Taking into account the dynamic nature of both production and project processes, a structure for the digital twin environment of a project-oriented enterprise was built, with its elements continuously synchronized with the real situation at the enterprise. The structure of such an environment is illustrated in Fig. 2, 3. This result is based on the proposed approach and is explained by the structure of interactions between the project and production activities of project-oriented enterprises, since project-production activities require the alignment of product release processes with project implementation processes. Thus, this concept creates advantages for any project-oriented enterprise by requiring the establishment of a digital environment (an environment of digital twins). In turn, this increases the level of information support for all management processes.

The development of the approach and the digital twin environment structure enabled the creation of a mathematical model for synchronizing digital twins in the process of combined planning of project and production activities – formulas (1)–(7). The model reflects both project and production processes as a single system of interaction between enterprise resources and projects. This result is explained by the application of a special method of combined planning of project-production activities in companies using digital twins of projects and production.

Based on the proposed mathematical model, a method for combined planning of project and production activities using digital twins of projects and production has been developed – formulas (8)–(10). Unlike traditional methods of planning project and production activities, where product release is driven by orders from project managers, the foundation of this method is a combined approach to planning both project and operational activities. In this method, requests for products are not generated at all. They result from the interaction between the digital twins of production and the digital twins of projects, which are continuously synchronized with the enterprise's production capacities and project capabilities. Based on this, a schedule for the production of the project's products is formed through simulation in the digital twin environment of the enterprise's production facilities. This original combination of project and production processes explains the obtained result – the method for combined planning of project-production activities in companies using digital twins of projects and production.

Unlike the works [13–19], where the tasks of planning project and production activities of enterprises are not considered as a unified system, the developed concept enables effective planning for project-oriented enterprises. This became possible through the use of digital twins as a single tool for managing both project and production activities of enterprises.

The proposed concept enabled the creation of digital project management tools capable of effectively planning both project and production processes while accounting for constant changes within the enterprise, which are synchronized with digital twins. This allowed solving the problem outlined in the work – the integration of operational and project activities in project-oriented companies under conditions of digital transformation.

The obtained results are a consequence of changing the planning concept for project-oriented enterprises in the fields of machine-building, aircraft-building, instrument-making, shipbuilding, and metallurgy. Instead of separating project and production processes, they were unified within a single concept of planning project-production activities for enterprises in these industries. This solution requires the use of new methods for planning both project and operational activities, methods that enable the coordination of the processes of forming project products with the processes of manufacturing various components for them.

The developed concept, approach, digital twin space representation, model, and method were practically tested at a number of enterprises [27, 29, 30]. The processes of producing components for projects and the projects themselves were represented as digital twins of real processes in the NadPlan software tool. This tool complements the Microsoft Project information base with tables containing information about operational activities, integrates these databases, and uses them to simulate options for manufacturing components for projects. This tool for combined planning of project-production activities implements a method for coordinating project and operational activities in the production of complex products in the fields of machine-building, aircraft-building, instrument-making, shipbuilding, and metallurgy. Moreover, it allows, within a unified information environment, not only to solve project planning tasks but also to coordinate work with customers of production activities unrelated to the enterprise's projects.

Practical results demonstrate that the created concept will increase the efficiency of enterprise management in the fields of machine-building, aircraft-building, instrument-making, shipbuilding, and metallurgy when implementing complex projects involving the production capacities of enterprises in these areas.

The limitations of this study are related to the type of enterprises that can apply the developed concept – machine-building, aircraft-building, instrument-making, shipbuilding, and metallurgy.

A drawback of this study is that the proposed approach has been applied only to the tasks of planning project-production activities for industrial enterprises in specific sectors of industry. Although such a fundamental idea as the use of digital twins in managing project tasks and production processes could have broader applications.

The development of this study involves expanding the application of digital twins to other project management tasks – risk management, configuration management, change management, logistics, operational work, and others.

7. Conclusions

1. A new approach to combined planning of project and production activities in project-oriented enterprises has been proposed. Given the dynamic nature of both production and project processes, the need arose to create a digital environment that would continuously synchronize with the real situation at the enterprise. Therefore, unlike existing approaches, the new approach to combined planning of project and production activities in project-oriented companies is based on the concept of digital twins of real objects and enterprise activity processes. It also includes the modelling of different work execution scenarios using digital twins. The tasks of managing project-production activities that require the creation of a new approach to project and production planning have been identified. Components that need to be developed within the framework of the new approach to combined planning of project and production activities in project-oriented companies have been defined. These include the digital twin environment, a synchronization model of project-production activity objects and processes with their digital twins, and a method for combined planning of project and operational processes, which serves as the basis for the enterprise's project-production activity plan.

2. The structure of the digital twin environment for projects and operational production has been developed. Unlike traditional construction methods, the digital twin environment includes both representations of production objects and representations of project processes. Since project-production activities require the coordination of product release processes with project implementation processes, the digital twin environment is divided into three areas: equipment for manufacturing project products; project tasks; and production activity outputs. These areas are dynamic and constantly changing, requiring synchronization of the digital twins located in these areas with real objects and processes. Based on the set task of planning project-production activities for enterprises, the informational content of the digital twins for these areas has been defined.

3. A mathematical model for synchronizing digital twins in the process of combined planning of project and production activities has been proposed, which ensures real-time alignment of the project plan with the production plan. The distinguishing feature of this model is that it describes both project processes and product manufacturing processes for the projects. It allows the determination of the time and volume of product release for projects, as well as the time and volumes of product usage in project tasks, based on the digital twins. The concept of a "zero-project" is introduced to account for direct orders for the enterprise's products. This was done to standardize the procedures for planning project-production activities, regardless of whether the products are needed for a project or for an external customer. It has been shown that conflicts between project planning and production planning in the model can be resolved using a special method of combined planning of project-production activities in companies with the use of digital twins for both projects and production.

4. A method for combined planning of project-production activities in companies using digital twins of projects and production has been developed. The method is iterative, linking the project planning process with the production planning process. Unlike traditional planning methods, its logic involves the sequential adjustment of the production plan to the project plan, and the project plans to the production plan, gradually converging towards a solution that satisfies the company's management. The method includes five stages, one of which implements the criterion for evaluating the plan decision, while the others are repeated as the plan approaches the desired outcome.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, whether financial, personal, authorship, or otherwise, that could affect the study and the results reported in this paper.

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Data availability

The manuscript has no related data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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