UDC 004.685.5
https://doi.org/10.32362/2500-316X-2023-11-1-70-80

RESEARCH ARTICLE

Logical-semantic definition of a production process digital twin

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Abstract
Objectives. A methodology currently being developed for generalizing and presenting knowledge about studied subject-oriented areas is based on a “model hypothesis” for determining the distinguished objects and their relationships. Such system models can be used in any information system to define the knowledge about subject-oriented areas. Systems engineering methods already make it possible to create information models of real objects supplemented by virtual components, and vice versa, i.e., models of virtual objects supplemented by real components. So, for example, the availability of information models of technological and production facilities and their connections with real equipment allow the creation and management of real-virtual production processes (PP) in accordance with Industry 4.0 methodologies. From a theoretical aspect, the development of system models of objects and their connections in subject-oriented areas is based on the problem of a formal consistent description (grammatical calculus) of the functional regularities of a given set of objects and their relationships. The purpose of the study is to develop an approach and principles of methodology for system modeling of production facilities and their connections to provide closed-loop control (forecasting, planning, accounting, regulation, etc.) in the production environments of machinery enterprises taking the form of their digital twins (DTs).
Methods. The basic provisions of the theory of sets and graph theory—in particular, the provisions of the theory of categories of sets—are used according to the formal logic and control theories. System Engineering methods are also applied in the organization and management of machinery production.
Results. The approach to the formation of a metastructure of production process digital twin (PPDT) based on the models of production facilities and their relationships is substantiated. The procedure and rules for constructing a PPDT system model are developed along with an approach to the structural and parametric identification of DT models, taking logical and semantic restrictions into account.
Conclusions. A presented example for identifying the basic set of objects of the organization of the PPDT based on the logical-semantic analysis of production activities and the provisions of the unified standards of the unified system for technological preparation of production of machinery production as a researched subject area confirms the main provisions of the proposed methodology for constructing the PPDT.

Keywords: system models, production processes, information systems, digital twin, decision support system, smart factory, planning system

• **Submitted:** 08.07.2022 • **Revised:** 19.09.2022 • **Accepted:** 14.11.2022

For citation: Rechkalov A.V., Artyukhov A.V., Kulikov G.G. Logical-semantic definition of a production process digital twin. *Russ. Technol. J.* 2023;11(1):70–80. https://doi.org/10.32362/2500-316X-2023-11-1-70-80

Financial disclosure: The authors have no a financial or property interest in any material or method mentioned.

The authors declare no conflicts of interest.

НАУЧНАЯ СТАТЬЯ

Логико-семантическое определение цифрового двойника производственного процесса

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Резюме
Цели. В настоящее время активно развивается методология обобщения и представления знаний об исследуемых предметно-ориентированных областях (ПОО) на базе «модельной гипотезы» определения выделяемых объектов и их связей. Такие системные модели определяют знания о ПОО в любой информационной системе. Методы системной инженерии уже сегодня позволяют создавать информационные модели реальных объектов, дополненные виртуальными составляющими, и наоборот, модели виртуальных объектов, дополненные реальными составляющими. Так, например, наличие информационных моделей технологических и производственных объектов и их связей с реальным оборудованием позволит создавать и управлять реально-виртуальными производственными процессами (ПП) в соответствии с методологией Industry 4. В теоретическом аспекте в основе разработки системных моделей объектов и их связей в ПОО лежит проблема формального непротиворечивого описания (грамматического исчисления) функциональных закономерностей данного множества объектов и их связей. Цель исследования – разработать подход и принципы методологии системного моделирования производственных объектов и их связей для замкнутого управления (прогнозирования, планирования, учета, регулирования и др.) в производственной среде машиностроительного предприятия в форме их цифровых двойников (ЦД).
Методы. Использованы базовые положения теории множеств, теории графов, и, в частности, положения теории категорий множеств, положения теории формальной логики, теории управления. Применены методы теории системной инженерии, методы организации и управления машиностроительным производством.
Результаты. Обоснован подход к формированию метаструктуры цифрового двойника производственного процесса (ЦД ПП) на основе моделей производственных объектов и их связей, разработаны порядок и правила построения системной модели ЦД ПП, разработан подход к структурно-параметрической идентификации моделей ЦД с учетом логико-семантических ограничений.
Выводы. Представлен пример идентификации базового множества объектов ЦД организации ПП на основе логико-семантического анализа производственной деятельности и положений единых стандартов Единой системы технологической подготовки производства для машиностроительного производства как исследуемой предметной области, подтверждающий основные положения предлагаемой методологии построения ЦД ПП.

Ключевые слова: системные модели, производственные процессы, информационные системы, цифровой двойник, digital twin, система поддержки принятия решения, smart factory, система планирования

• **Поступила:** 08.07.2022 • **Доработана:** 19.09.2022 • **Принята к опубликованию:** 14.11.2022

Для цитирования: Речкалов А.В., Артюхов А.В., Куликов Г.Г. Логико-семантическое определение цифрового двойника производственного процесса. *Russ. Technol. J.* 2023;11(1):70–80. https://doi.org/10.32362/2500-316X-2023-11-1-70-80

Прозрачность финансовой деятельности: Авторы не имеют финансовой заинтересованности в представленных материалах или методах.

Авторы заявляют об отсутствии конфликта интересов.

INTRODUCTION

Many societies are undergoing processes of fundamental changes determined by the requirements of the fourth industrial revolution (Industry 4.0), which implies an active transformation of existing systems of industrial production, technology management, transportation, supply of resources, etc.[1] As noted in [1], the basis and primary infrastructure of this new way of life is formed by information technology (IT). At the same time, within this framework, it is of fundamental importance to develop a comprehensive, integrated understanding of how technologies will change our lives, implying a transformation of the environment of our understanding[2]. According to research conducted by the analytical company IDC, by 2025 the share of the digital economy will grow to 58.2% in the total volume of the world economy [2].

In the context of ever more complex industrial technologies, increasing competition, and accelerating the development of new technology, the introduction of new methods of coordination and interaction both in the external environment and within individual enterprises is becoming not only an urgent need, but also the key to the vital transformation of industrial models [3]. Digital technologies significantly expand interaction possibilities, increase production and supply efficiency, improve the distribution and use of resources, as well as implementing new methods of inventory management. This implies the concomitant possibility of carrying out a system-wide optimization of the management of production processes (PP) and the use of resources.

In recent years, the development of IT is increasingly focused on the formation of technologies for the development and use of a digital twin (DT). The system of DTs, unlike traditional solutions focused on periodic recalculations of plans, can take into account a variety of emergency situations that can be predicted by analyzing a huge data stream. The ability to process and analyze data on the current state of production in accordance with plans in real time allows one to quickly respond to deviations in production and eliminate emerging problems.

Thus, the DT system will allow modeling not only the state of the PP, but also its dynamics. The main task of the digital system is to provide real-time control of all factors affecting the PP[3].

1. PRODUCTION PROCESS DIGITAL TWIN CONCEPT

The concept of a DT in the science and machinery production is quite new and does not yet have an established terminology [4]. For example, the article entitled “Digital Twin of Organization, DTO”[4] presents several options for formulating the concept of a DT:

- a software analogue of a physical device for simulating the internal processes, technical characteristics and behavior of a real object under the influence of interference and the environment;
- a virtual prototype of real production assets—wells, turbines, wind electrical turbines, etc.;
- a digital representation of an object sufficient to meet the requirements of a set of use cases;
- a digital model of a specific physical element or process with connections to data to support the convergence of physical and virtual states at an appropriate rate;
- a model that describes as accurately as possible the real cause-and-effect relationships between the production, economic, financial and organizational indicators of the company.

A more general formulation can be given: “A digital twin is a digital representation of an object or system of the real world”[5]. If we define the concept of a DT fully, then a DT is a digital system representation of a real object, process or system in a virtual environment.

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[1] Artyukhov A.V. *Methods and models of the organization of the production process of a multi-product machinery enterprise as a control object*: Cand. Sci. Thesis (Eng.). Samara; 2017. 20 p. (in Russ.).

[2] Khuzmiev I.K. Information technology is the infrastructure of the fourth industrial revolution. *Russia: trends and development prospects.* 2017;12(3):274–277 (in Russ.).

[3] Within the framework of this article, we mean the production process.

[4] Digital Twin of Organization, DTO. https://www.tadviser.ru/index.php/Статья:Цифровой_двойник_(Digital_Twin_of_Organization,_DTO). Accessed September 23, 2022 (in Russ.).

[5] Digital Twin. https://www.gartner.com/en/information-technology/glossary/digital-twin. Accessed September 23, 2022.

It is believed that initially the concept of a DT in management was reported by Michael Greaves at the Product Lifecycle Management forum at the University of Michigan in early 2002. The concept was based on the mutual correspondence and interaction of the physical system and its virtual display based on virtual interconnection [5].

If initially there appeared DTs of products that associatively determine the means and objects of labor (OLs) in the virtual space of the enterprise, then, when forming an intellectual enterprise (Smart Factory) or DT of a production system (DTPS) it becomes necessary to formalize the production process digital twin (PPDT) [6]. At the same time, the PP can be represented as a process of interaction of means of labor (MLs), OLs, and labor resources (LRs) in space and time in order to obtain the result of the process, i.e., the product (Pr)[6] (Fig. 1).

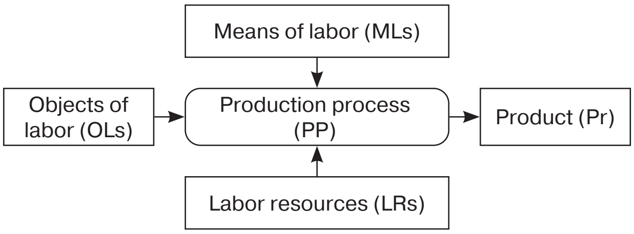

Fig. 1. Relationship of the elements of the production process

The OLs as PP elements comprise materials, components, semi-finished products, parts and assembly units; in essence, and their models are DT-components (Component Twin). Models of equipment, tools and LPs are DTs of a resource (Asset Twin). Models of the result of the PP are the product DT (System Unit Twin). Models of the process of interaction of these elements are the PPDT (Process Twin) [5]. As a whole, the totality of these elements represents DTPS (Fig. 2).

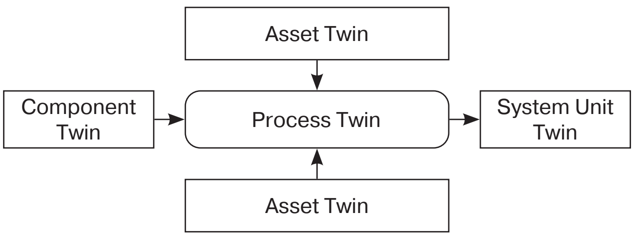

Fig. 2. Relationship of DTPS elements

As a result, we can agree with the following formulation of the DTPS concept: "The digital twin of a production system is a digital model that is constantly updated and changed as its physical counterpart changes in order to synchronously present data on the status, operating conditions, product configuration, and state of resources"[7]. The definition of a DT as a software-hardware complex that implements a complex dynamic model for researching and managing the activities of a sociotechnical system allows us to represent the PP as a control loop, where the PP itself acts as a control object, and its DT acts as a control process with feedback (Fig. 3).

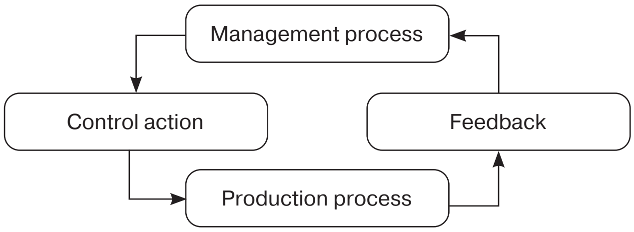

Fig. 3. PP as a control loop

Proceeding from this provision, the principles for the formation of a PPDT based on models of traditional automatic control systems can be formulated as follows: a DT should reflect the current state of the PP and carry out a forecast of this state in the form of phase trajectories (in the space states) of plans based on a detailed analysis of perturbing influences, with variants developed for the behavior of the system along with recommendations for decision-making. In this case, all actions are performed in real time.

At the same time, it is noted that for the practical implementation of the DT concept, the most difficult is the PPDT model, which implements a number of fundamental functions [6, 7]:

- real-time display of PPs occurring in the PS;
- carrying out calculations for making managerial decisions;
- implementation of decision support processes, for example, "what if" based on modeling the behavior of PPs.

2. PPDT STRUCTURE

The PPDT, defined as a reflection of the process of interaction between MLs, OLs, and LRs in order to obtain Pr, basically contains five groups of models:

- a group of product models, including the composition and relationships of OLs within the product, including quantitative, temporal, cost and quality characteristics that determine the use value of the result of the PP;
- a group of models of labor objects, including models of materials used in the PP, semi-finished products,

[6] Artyukhov A.V. *Methods and models of the organization of the production process of a multi-product machinery enterprise as a control object*: Cand. Sci. Thesis (Eng.). Samara; 2017. 20 p. (in Russ.).

[7] PNST 429-2020. *Smart manufacturing. Production digital twins*. Part 1. *General provisions*. Moscow: Standartinform; 2020. 8 p. (in Russ.).

purchased components, as well as parts and assembly units that are in the process of production, fully embodied in the product;

- a group of models of labor means, including models of characteristics and parameters of each separate resource within the framework of the participation of resources in a technological operation;
- a group of models of LRs, including models of characteristics and parameters of each individual resource that determine the participation of resources in a technological operation;
- a group of models of technological processes as a set or sequence of technological operations, including quantitative, temporal, cost and qualitative characteristics of the relationship between OLs and resources.

Taking into account that in this case the MLs, OLs, LRs, and Pr models contain only data necessary for the PP implementation, these models reflect the technological process that determines the PP static (structural) organization. The concept of “static” in this case is relative. Although all the above models support the changes inherent in the corresponding physical objects, these changes are reflected within the framework of the PPDT regardless of its dynamic characteristics. Accordingly, the formulation of the concept of a technological process as a complex of models of a technological process, containing information about technological processes as targeted actions in order to change and (or) determine the state of the OL (which can be attributed to the finished product, its component or to the methods of processing, shaping and assembly[8]), corresponding to the content of the static model of the PP or the DT of the PP organization.

In general, models are defined as static, describing objects in stationary modes of their operation, and dynamic, describing transient processes. The dynamic nature of the PPDT model is reflected in the standard: “Digital twin of production allows real-time production control to dynamically manage production volume and meet the production plan”[9]. In this case, the time requirements of the product are input variables, while the requirements for other resources are output variables; the model describes the transient mode of the PP.

Quantitative and temporal characteristics of the interaction of resources in the PP, which are determined by the demand for finished products, form the initial data for the planning model or DT of planning the PP.

The structure of the planning model primarily depends on the structure of the initial data generated from the results of demand planning. An analysis of planning and management models based on descriptions of manufacturing resource planning (MRP) algorithms and enterprise resource planning (ERP) systems allows two types of demand data to be distinguished—i.e., volume-calendar and order-based—as well as to determine a set of PP management models. Correspondingly, the DT of PP planning can be represented by two linked DTs: the DT of volume-calendar planning of PP and the DT of order-based planning of PP, as well as the complex of feedback and control models by the DT of control of PP [8].

The volume-calendar planning DT implements the following main functions:

- enlarged planning of production capacities;
- enlarged planning of purchased products and materials;
- creation of the main production calendar.

The DT of order-by-order planning implements the following main functions:

- planning production orders;
- power distribution planning;
- planning orders for the repair of products;
- planning orders for storage and distribution;
- planning purchase orders.

The DT of production control implements the following main functions:

- production accounting;
- decision support;
- control of direct production costs;
- quality control management;
- tool distribution control.

The analysis of ERP systems can also be used to differentiate the PP as a control object in the form of a set of internally homogeneous, relatively independent, but interconnected processes:

- PP;
- product repair process;
- process of storing OLs;
- process of formation of costs;
- quality control process;
- power distribution process;
- process of allocating labour;
- tool allocation process.

Correspondingly, the expanded model of the PPDT takes the form of a set of interconnected control loops, which can be defined as functional areas of a DT (Fig. 4).

Thus, the PPDT comprises a set of DTs:

- PP organization;
- volume-calendar planning of production;
- order-by-order production planning;
- production management.

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[8] GOST 3.1109-82. *Interstate standard. Unified system of technological documentation. Terms and definitions of basic concepts*. Moscow: Izdatel’stvo standartov; 1981. 15 p. (in Russ.).

[9] PNST 429-2020. *Smart manufacturing. Twins of digital production*. Part 1. *General provisions*. Moscow: Standartinform; 2020. 8 p. (in Russ.).

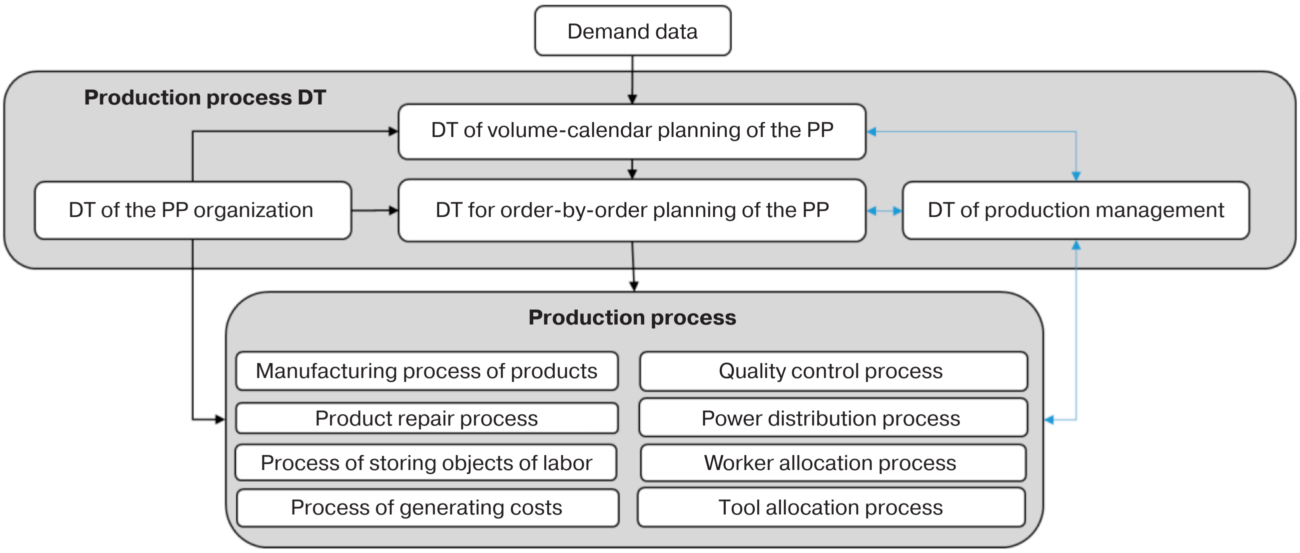

Fig. 4. Expanded top-level structure of the PPDT

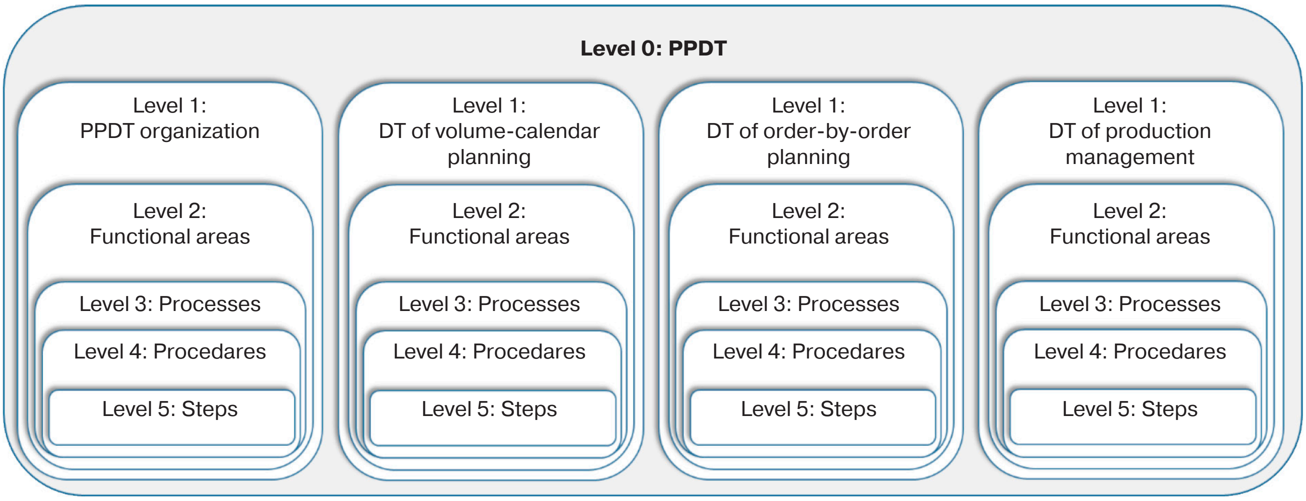

Fig. 5. PPDT generalized structure

Each DT consists of control loops of the corresponding functional areas. Within the framework of a detailed description of the models, each functional area can contain a three-level structure: processes, procedures, and steps. Correspondingly, the PPDT comprises a set of models formed on the basis of the composition of the functions of each DT, as well as the corresponding functional area and hierarchical description of the models (Fig. 5).

3. PPDT IDENTIFICATION

In accordance with Ashby's law of requisite variety [9], optimal control is achieved under the condition that the variety of the control action corresponds to the variety of the controlled one. This property is provided by two factors: full knowledge of the behavior of the controlled system on the part of the control system and the ability to turn this knowledge into an adequate reflection within the DT, i.e., provide the generated models with the requirements of identifiability and traceability. Identifiability is a property that a model must satisfy in order to be able to draw accurate inferences[10]. A model is identifiable if it is theoretically possible to know the true values of the main parameters of this model after receiving an infinite number of observations from it. Typically, a model is identifiable only under certain technical constraints, in which case the set of these requirements is referred to as identification conditions.

The concept of system identification can be defined as a set of methods for constructing mathematical models of a dynamic system based on observational data[11]. Another

[10] *Identifiability*. Wikipedia. https://ru.wikibrief.org/wiki/Identifiability. Accessed September 09, 2022 (in Russ.).

[11] *Systems identification*. Wikipedia. https://en.wikipedia.org/wiki/System_identification. Accessed September 09, 2022 (in Russ.).

definition is as follows: identification is the process of constructing models of objects of various nature. In this case, the identification process consists of two interrelated stages: identification of the structure of models and identification of parameters in models of the selected structure. When constructing the model structure (or a set of competing or complementary structures), a priori information about the object is used. For each class of objects, banks of structures with related information are formed[12].

Coming from the features of the content of the DT, the identification process should be based on the following fundamental provisions:

- *Identification of the DT of the organization of production*, as containing a static model of the PP, is based on the analysis of the structure and parameters of the technological process documented in the standards of the Unified System of Technological Documentation (USTD).
- *Identification of the DT of the volume-calendar process and the DT of the order-by-order planning process* is based on the structure of processes defined in the international standards for production planning and management by the American Production and Inventory Control Society, the MRP/ERP methodology and the parameters determined based on the analysis of the totality of PPs.
- *Identification of the DT of production management processes* in terms of production accounting, analysis and decision-making processes is based on the Ashby principles [9], which involve ensuring maximum detail of the planning and accounting characteristics of the PP that determine the maintenance of homeostasis of the PS.

Thus, in order to ensure the identifiability of PPDT models, it is necessary to determine the structure and set of parameters that provide the identifiability of each type of PP objects (MLs, OLs, LRs, and Pr), interaction processes, and a list of technical restrictions that determine the conditions for identification.

The approach to the identification of the structure of the PPDT based on the provisions of the theory of sets, and, in particular, the provisions of the theory of categories, as well as the provisions of formal logic, will make it possible to form methods for identifying the metastructure of the DT based on the formalization of expert knowledge. At the same time, it is important to note that the conceptual scheme of the top-level representation of the DT structure, as a rule, consists of semantic attributive descriptions in the form of hypertext and production knowledge bases that form the basis of the structure of production management expert systems.

[12] Boyko R.S. On modeling discrete-continuous processes. *Young scientist*. 2010;4(15):93–98 (in Russ.).

4. AN APPROACH TO DT IDENTIFICATION: CASE STUDY OF A DT OF A PP ORGANIZATION

Let us consider an approach to the identification of the DT of the PP organization based on the formalization of knowledge formulated in the standards of the Unified System for Technological Preparation of Production (USTPP)[13, 14] for determining the semantic boundaries of the studied subject area of the PP based on text documents using a graph-analytical representation of PP objects. In this case, MLs (*ML*), OLs (*OL*), LRs (*LR*), and Pr (*Pr*) comprise sets of objects, while the PP represents sets (relations) of morphisms. At the same time, if we exclude from consideration the dynamic characteristics of the PP (amount and time), then we form a graphical representation of the PPDT organization or a graph of the ontological model that defines the boundaries of the subject area and the structure of the PPDT organization. For a more correct representation of the structure of objects in the MLs, we can allocate capacities (equipment, warehouses, and production premises) (*Caps*) and tools and fixtures (*Tools*) (Fig. 6).

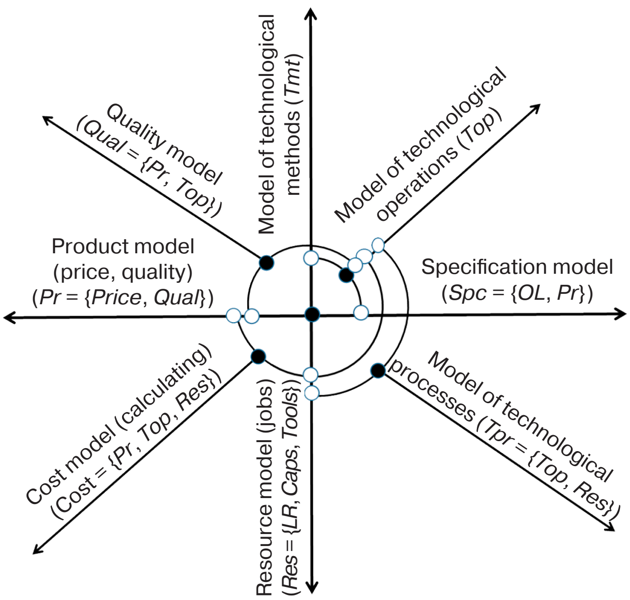

Fig. 6. Graphical representation of the structure of the DT of the PP organization

At the first stage, the textual and tabular representation of the data of the sets of objects reflected in the USTD standards is analyzed. For example, the set of technological methods

[13] GOST 3.1109-82. *Interstate standard. Unified system for technological documentation. Terms and definitions of main concepts*. Moscow: Izdatel'stvo standartov: 1981. 15 p. (in Russ.).

[14] GOST 14.004-83. *Technological preparation of production. Terms and definitions of basic concepts*. Moscow: Izdatel'stvo standartov; 1983. 8 p. (in Russ.).

Table 1. Structure of the system model of the PPDT organization. Part 1

Objects of labor models		Technological methods	Models of technological operations
Objects of Labor (OL)	OL structure		
Item Material Main material Auxiliary material Semi-product Blank Initial workpiece Stamped product Casting Forging Accessory Part Assembly unit Assembly kit Ready product Aggregate Refurbished product Blend Alloy Die block Defective product Technological losses Secondary material resources Used waste Unused waste Irretrievable waste	OL identification: A – Anonymous OL N – Numbered OL B – Numbered batch of OL C – Custom OL Traceable entry type: A – A A – B A – N A – C B – B B – N B – C N – N N – C C – C	Casting Molding Cutting material Forging Volumetric stamping Sheet stamping Surface plastic deformation Machining Thermal processing Electrophysical processing Electrochemical processing Electroplating processing Locksmith processing Assembling Welding Riveting Soldering Gluing Coating Technical control Tests Acquisition Dismantling Transportation Storage Repair Waste recycling	MTO1 MTO2 MTO3 MTO4 MTO5 MTO6 MTO7 MTO8 MTO9

$Tmt = \{tmt_1, tmt_2, \ldots, tmt_n\}$ represents a list of elements of the structure and characteristics of the methods of interaction of OLs, while the set of specifications $Spc = (spc_1, spc_2, \ldots, spc_n)$ represents an interconnected list of OLs: $OL = (OL_1, OL_2, \ldots, OL_n)$, i.e., purchased materials, semi-finished products, purchased workpieces, as well as manufactured parts and assembly units that are in operation[15]. At the same time, for each pair of elements of the set *Spc* and the set *Tmt*, a set of morphisms is formed: technological operations $Top = \{top_1, top_2, \ldots, top_n\}$, i.e., $Tmt \subset Top$ and $Spc \subset Top$.

The set of production workers with indication of their professions and qualification characteristics $LR = \{LR_1, LR_2, \ldots, LR_n\}$, the set of capacities $Caps = \{cap_1, cap_2, \ldots, cap_n\}$, the set of tools $Tools = \{tool_1, tool_2, \ldots, tool_n\}$ are included in the set resources (jobs) $LR \subset Res$, $Caps \subset Res$, $Tools \subset Res$. Other sets of the presented structure of the PPDT organization are formed similarly.

At the next stage, the characteristics of each object of the set are generated on the basis of the graph-analytical and syntax analysis of the USTPP documents. The result of identification of models of the PPDT organization is the formal structure of the system model of the PPDT organization (Tables 1 and 2)[16].

The PP organization model comprises a metamodel that combines the elementary models. The metamodel of the organization of the PP as presented in Tables 1 and 2 also reflects the variety of functional interconnections of the elements of the PP: elementary OLs, elementary MLs, and elementary technological processes (operations), as well as elementary interoperational PPs that determine the composition and content of the PPDT organization.

CONCLUSIONS

The main results obtained in the presented work are as follows:

1. Formulation of logical-semantic requirements for the creation of system models of logistics, production, service, and other processes in the form of their DT comprising the necessary conditions for constructing

[15] GOST 3.1109-82. *Interstate standard. Unified system for technological documentation. Terms and definitions of main concepts*. Moscow: Izdatel'stvo standartov; 1981. 15 p. (in Russ.).

[16] Artyukhov A.V. *Methods and models of the organization of the production process of a multi-product machinery enterprise as a control object*: Cand. Sci. Thesis (Eng.). Samara; 2017. 20 p. (in Russ.).

Table 2. Structure of the system model of the PPDT organization. Part 2

Model of organizational structure	Workplace models		Models of organization of technological process operations	Models of interoperational processes
	Workplace structure	Workplace type		
Divisions: - warehouses of purchased OL - warehouses of sold OL - warehouses for obsolete OL - warehouses of OL in production - warehouses of finish-processed and ready-to-assemble OLs - own consignment warehouses - consignment warehouses not own - production shops - production sites	Group of mechanisms Mechanism Group of workers Worker	Simple worksplace Multi-station workplace Integrated workplace	Model of a single-object non-reconfigurable process Model of a single-object reconfigurable process Model of a multi-object reconfigurable process	Models for the formation of production batches of OL Models for the formation of transfer batches of OL Models for the formation of safety stock Models of processing-waiting OL

a cybernetic control model with feedback to meet the required stability margins and quality.

2. Based on the formalization of the results of the logical-semantic analysis of the PP and the management process, an approach has been developed to the formation of a structural-parametric model of the PPDT, taking into account the existing external restrictions (boundaries).
3. Based on the above approach, the metastructure of the PPDT has been developed; it has been shown that the existing structures of production facilities and PP can be coordinated (harmonized) taking into account the requirements of the international standards ISO “Smart Manufacturing.”[17]
4. It is shown that the application of the main provisions of the theory of sets—and, in particular, the provisions of the theory of categories of sets and the provisions of formal logic—forms the basis for an approach to identify the model of the PPDT based on the formalization of expert knowledge.
5. A case study of identification of the PPDT organization based on the logical and semantic analysis of the provisions of the USTPP standards is presented.

Authors’ contributions

A.V. Rechkalov has proposed an approach to the digital transformation of automated production control systems of operating machinery enterprises (ME) based on the formalization of the logical-semantic model of the production process (PP). He showed that the existing metastructures of production facilities and PP can be harmonized with the requirements of ISO “Smart Manufacturing.”

A.V. Artyukhov has developed a methodology and algorithm to design system models of planning, logistics, production, service, and other ME processes in the form of their digital twins (DT) based on structural and parametric identification under the condition of their traceability and controllability. He showed that on the basis of ME PPDT it is expedient to form metastructures of the distributed (parallel) PP for ME united in a machinery holding. He proposed an approach to the formation of the structure of an information management system with feedback.

G.G. Kulikov has proposed to use the basic provisions of the theory of sets, in particular, the provisions of the theory of categories of sets and the provisions of mathematical logic for a formal description of the PPDT.

[17] https://www.iso.org/standard/81277.html. Accessed September 23, 2022.

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Translated from Russian into English by Evgenii I. Shklovskii
Edited for English language and spelling by Thomas A. Beavitt

MIREA – Russian Technological University.
78, Vernadskogo pr., Moscow, 119454 Russian Federation.
Publication date January 31, 2023.
Not for sale.

МИРЭА – Российский технологический университет.
119454, РФ, г. Москва, пр-т Вернадского, д. 78.
Дата опубликования 31.01.2023 г.
Не для продажи.