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RESTORATION AND TRANSFORMATION OF HIGH-TECH MACHINE BUILDING INDUSTRY BY IMPLEMENTING THE PRINCIPLES OF THE CALS-CONCEPT IN THE CONTEXT OF INDUSTRY 4.0 DEVELOPMENT

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The object of this study was the processes of restoration and transformation of high-tech engineering using the principles of Industry 4.0 and CALS-concept. The problem of identifying ideas, concepts, tools and developing the principles of their application for the restoration and transformation of high-tech engineering has been solved. It is shown that the restoration of high-tech engineering, in countries affected by hostilities, is advisable to carry out using the CALS concept. The top priority CALS technology and systems have been identified. An opportunity to jump from Industry 2.0 to Industry 4.0. for countries in which mechanical engineering has suffered greatly as a result of hostilities has been shown. The principles of restoration and transformation of high-tech engineering by implementing the principles of CALS concept in the context of Industry 4.0 development have been developed. The infrastructure of the participants of the life cycle of machine-building products is proposed. A model for optimizing the production program of the defense-industrial complex has been built. The model takes into consideration the nonlinearity associated with the optimization of the production program, as well as the stochastic nature of changes in the model parameters. An adaptive approach is proposed that makes it possible to optimize the production program according to the model even for specialists without special mathematical training. The priorities of post-war reconstruction of high-tech engineering have been defined. This study will make it possible to transform and restore the machine-building industry destroyed as a result of hostilities as soon as possible. The condition for the practical use of this study is to stop the hostilities

Keywords: mechanical engineering, Continuous Acquisition and Life-Cycle Support, Industry 4.0, Shared Data Environment, optimization model

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1. Introduction

Around the world, the process of implementing the main achievements of Industry 4.0 is in full swing – the fourth industrial revolution. The main innovations of Industry 4.0 include big data, machine learning, the Internet of Things, robotics, digital twins, etc. The regional unevenness of the implementation of these components of Industry 4.0 creates great risks for entire regions of the planet. Thus, with the development of the main achievements of Industry 4.0, countries with low rates of its implementation can be excluded from the global logistics chains of production and supply. Due to the high level of automation and robotics in developed states, countries with low rates of implementation of Industry 4.0 may lose entire sectors of the economy, due to the leveling of their main advantage – cheap labor. Thus, the fourth industrial revolution brings not only opportunities but also significant challenges.

Mechanical engineering is the locomotive of industry because it launches work of many related industries, such as metallurgy, polymer production, etc. At the same time, mechanical engineering is one of the best points of application of the main innovations of Industry 4.0, specifically robots, cobots, the Internet of Things, big data technologies, digital twins. Moreover, these innovations can be applied both in machine-building production and at all stages of the life cycles of high-tech machine-building products.

Thus, the development of scientific principles of uniform transformation of high-tech engineering in different regions of the planet is an actual scientific direction. In addition, the relevance of the topic is in the need to develop scientific principles of restoration, using the innovations of Industry 4.0, mechanical engineering in countries affected by hostilities.

2. Literature review and problem statement

The basic concepts and principles of the Fourth Industrial Revolution are reflected in many sources. Thus, in [1] the ideas of the fourth industrial revolution are formed as a holistic concept that will ensure the transition of the world economy to a qualitatively new level. The cited work does not contain details and experience of its implementation in various industries and regions of the planet, which is due to the fact that the cited work appeared at the beginning of the era of the fourth industrial revolution.

The information document [2] summarizes the world experience in implementing the principles of the fourth industrial revolution. It is shown that the so-called «beacons» are important in the implementation process, that is, the most innovative enterprises, the experience of which should be disseminated. In [2], there is not enough attention paid to the processes of integration of Industry 4.0 innovations with other systems and technologies for maintaining the life cycles of high-tech machine-building products. This may be due to the fact that [2] is not a specialized study but concentrates on investigating the development of Industry 4.0 as a whole.

Work [3] defines the sustainability functions of Industry 4.0. However, the issues of transformation of industry, specifically mechanical engineering to the level of Industry 4.0, are not paid enough attention.

Paper [4] shows that Industry 4.0's current manufacturing trend offers new key technologies, such as cyberphysical systems, the Internet of Things, additive manufacturing, and big data analytics. These new technologies directly or indirectly contribute to sustainability. It is necessary to determine various factors of implementation since this is the introduction of sustainable development methods in Industry 4.0. The cited research aims to develop the basis of sustainable development practices for Industry 4.0 for the micro, small and medium-sized enterprises sector. However, work [4] does not cover powerful machine-building enterprises.

Research work [5] provides guidelines for businesses seeking to build recycling production and thus achieve sustainable development goals by implementing Industry 4.0 principles. The scientific results reported in [4, 5] should be further developed for use in high-tech machine-building enterprises.

Work [6] concentrates on how, through Industry 4.0 principles, to move from the linear life cycle of the product «production-use-recycling» to the recycling life cycle. This can provide a simultaneous increase in the profits of the enterprise and a decrease in the negative impact on the environment.

The scientific results reported in works [5, 6] do not consider the processes of transition to the recycling life cycle of products under the conditions of transformation and restoration of high-tech engineering. This is due to the fact that works [5, 6] are focused on the industry of developed countries.

Paper [7] presents the essence, genesis, and development trends (Product Life-Cycle Management) of PLM-systems. These advanced tools support work of engineers at all stages of the product life cycle. They are especially useful and even necessary in the development of products that combine various areas of technology, that is, products with mechanical, electrical, electronic, IT components, etc. for PLM systems. Paper [7] presents the essence, genesis, and trends in the development of PLM systems. The authors selected examples of the use of Industry 4.0 technology in PLM systems, including the industrial Internet of Things, virtual and augmented reality, and digital twins. Work [7] should be complemented by the principles of using continuous acquisition and lifecycle support (CALS) concept as the theoretical foundation for the construction of PLM systems. CALS concepts in [7] are not paid enough attention. This is due to the tendency in the management of high-tech machine-building products to concentrate on the practical aspects of PLM. Moreover, this happens without the systematic use of the scientific and methodological tools of the CALS concept.

In [8], a comparative analysis of the initiatives for the implementation of Industry 4.0 at the national level in different countries was carried out. The factors of successful implementation of Industry 4.0 in the EU Member States are considered. Based on the analysis of the European experience of digital transformations of industry and national economies, an attempt was made to highlight the key focuses of such transformations. However, it should be noted that the results of the cited work can be used only partially during the post-war reconstruction to restore the destroyed machine-building industry during the military operations in Ukraine. In addition, [8] does not consider the implementation of the CALS concept as one of the factors in accelerating the implementation of Industry 4.0 achievements.

Paper [9] explores the spatial distribution of Industry 4.0, taking into consideration factors specific to the region and technology. By focusing on patent data for the four technologies that are the backbone of Industry 4.0, the authors provided evidence of their uneven distribution by region. The analysis confirms the role of regional absorption ability, cognitive and spatial proximity as drivers of Industry 4.0 knowledge flows but also points to important differences between these technologies. Technological capabilities and spatial proximity are determined to have a stronger impact on the proliferation of robots and 3D printing, while big data and the Internet of Things tend to be more spatially distributed.

The issue of the introduction of Industry 4.0 in mechanical engineering is not paid enough attention in articles [8, 9] due to the fact that they are concentrated not on the sectoral but on the geographical distribution of the intensity of the implementation of Industry 4.0.

Study [10] shows that digital twins reflect real objects with their data, functions, and communication capabilities in the digital world. As nodes in the Internet of Things, they provide networking and thus automation of complex value chains. The use of simulation methods makes them suitable for experiments, so digital twins become experimental digital twins. Initially, experimental digital twins interact with each other exclusively in the virtual world. The resulting networks of interacting experimental digital twins' model different application scenarios are modeled on virtual test benches, providing new foundations for integrated modeling-based system engineering. Thus, complete digital representations of relevant real assets and their behavior are consistently created. A network of experimental digital twins combined with real objects make it possible to create hybrid systems in which experimental digital twins are used in combination with real equipment. Thus, complex control algorithms, innovative user interfaces, and intelligent systems are implemented.

The issue of creating experimental twins of high-tech machine-building products, highlighted in work [10], require specifying in terms of specific machine-building products.

There were no articles that would consider the principles of transformation of high-tech engineering, and especially the processes of restoration of the destroyed, for example, as a result of hostilities, machine-building industry based on Industry 4.0 principles. Therefore, scientific issues of restoration and transformation of high-tech engineering using the principles of Industry 4.0 and CALS concepts need to be developed.

3. The aim and objectives of the study

The aim of this study is to develop conceptual solutions for the restoration and transformation of high-tech engineering using CALS technologies and systems and innovations of Industry 4.0.

This will make it possible to transform and restore the machine-building industry destroyed as a result of hostilities as soon as possible.

To accomplish the aim, the following tasks have been set:

– to analyze CALS technologies and systems for transformation and restoration of mechanical engineering, as well as maintenance of life cycles of high-tech machine-building products;

– to analyze the main innovations of Industry 4.0 for their application for the transformation and restoration of mechanical engineering;

– to synthesize the principles of restoration and transformation of high-tech engineering through the implementation of the CALS concept in the context of the development of Industry 4.0.

4. The study materials and methods

The research materials were ideas, tools, innovations, CALS concept technologies, and Industry 4.0. The object of this study was the processes of restoration and transformation of high-tech engineering using the principles of Industry 4.0 and CALS-concept. The study is based on the hypothesis of the jumping nature of the transition from one technological structure to another. The assumption is made about the possibility of moving from Industry 2.0 immediately to the level of Industry 4.0, passing the level of Industry 3.0 and 3.0+. The research methods were a systematic analysis of current trends in the development of Industry 4.0 and the CALS concept. Next, we used heuristic methods of synthesis for the principles of restoration and transformation of high-tech engineering by implementing the principles of the CALS concept in the context of the development of Industry 4.0.

5. Results of studying the restoration and transformation of mechanical engineering using the principles of Industry 4.0 and CALS concept

5. 1. Results of studying the CALS technologies and systems for transformation and restoration of mechanical engineering

Most scientific and technical projects are multidisciplinary in nature, for example, in the program to support scientific projects of the European Union Horizon Europe [11] is very much appreciated by multidisciplinary in projects. This requires the cooperation of specialists of different profiles, that is, the creation of multidisciplinary project teams. However, in insufficiently technologically advanced countries, most scientific and design teams are narrow-profile. That is why it is very important to study and implement the experience of creating multidisciplinary project teams.

The multidisciplinary team of the project is characterized as the most effective in the organization, focused on team activity, and functioning in a changing and poorly predictable market [12]. It brings together specialists from a number of organizational units or partner organizations whose competence makes it possible to find and implement the most optimal solution to a complex problem. The combination of abilities of team members that complement each other creates a synergistic effect that determines its high potential.

Multidisciplinary groups (MDGs) or Integrated Project Teams (IPTs) are used to combine competencies and resources from different organizations to effectively solve specific problems through joint work [13].

The structure, composition, and role of MDG will vary depending on the strategy and objectives of the project and the level of integration between the customer and the contractor. With proper use, MDG speeds up the execution process and improves the quality of the project by replacing long formalized procedures for exchanging information with direct personal work. It is assumed that MDG is available as a resource at all stages of the life cycle of the scientific and technical project.

To restore the machine building destroyed by the war, it is advisable to assess the personnel potential of Ukraine.

The issues of the creation and development of MDGs and IPTs in engineering and computer science are not covered enough. Therefore, there is a wide area for research [14–16] in this direction. MDG work can be carried out both through personal contacts and using another concept that is offered in [13] – shared data environment (SDE).

SDE is a collection of software and hardware that supports information exchange and allows data to be controlled, accessed, and distributed among all participants in the life cycle of high-tech machine-building products during its existence. Services of the shared data environment should be available throughout the life cycle of a high-tech machine-building product. In the development process, MDG uses a shared data environment to accelerate and improve research and design processes. At the operational level, SDE provides rapid controlled access to technical information of a scientific and technical project and a high-tech machine-building product at all stages of their life cycles [13].

From a technical point of view, SDE is an automated service that provides the implementation and maintenance of data resources used by at least two combat support applications. Services include identification of general data, modeling of physical data, database segmentation, development of procedures for data verification and maintenance, as well as database reengineering for the use of the common data environment [17].

Along with SDE, there is a common data environment (CDE). It is understood as a repository of digital documentation of the project, usually located on cloud servers [18–20]. The concept of CDE is associated with construction projects, namely, closely related to the concept of their information support. Therefore, for information support of high-tech machine-building projects, we shall use SDE.

Fig. 1 shows the infrastructure of participants in the life cycle of high-tech machine-building products, united by a common data environment.

The further development of Fig. 1 requires filling its content with specific participants in the life cycles of high-tech machine-building products characteristic of a particular industry, country, or region.

Building a shared data environment of a scientific and technical project – SDE, which is a prerequisite for the implementation of the above ideas, requires a database of high-tech machine-building products, which, in turn, requires the availability of an appropriate data model. The CALS concept proposes the NATO CALS Data Model. NATO CALS Data

Model is a flexible means of semantic data breakdown that generates samples of high-tech machine-building products during their life cycles. It offers a breakdown of the product structure for both design and production and logistics support. The issue of using NATO CALS Data Model for high-tech engineering is well covered in [21–24].

Another concept is closely related to the concept of the shared data environment – information management. Information management is engaged in the organization of processes of processing, storage, distribution, archiving or disposal of information. Depending on the application, there are many areas of data management – from personal data management to intelligence data management [25–27]. An interesting concept of data management of high-tech machine-building products is presented in [13] – Through Life Information Management (TLIM)). TLIM focuses on how to collect and transmit technical information necessary for participants in the life cycle of high-tech machine-building products for its creation, acquisition, technical support, and disposal. As products become more complex, it becomes more difficult to manage the information needed for maintenance, especially in the process of upgrading the product. Both the complexity and the amount of information required for maintenance are growing. This information begins to be created at the beginning of the life cycle of a high-tech machine-building product, and it must be managed throughout the life cycle. Such information includes: configuration data, assembly drawings, connection diagrams, test requirements, data on special tools and test equipment, diagnostic data, information about spare parts, types of failures, etc. The absence of any of this information can lead to the suspension of the functioning of high-tech machine-building products at different stages of its life cycle. Feedback between different lifecycle participants is also needed to track maintenance costs and address the causes of downtime.

Previously considered concepts, namely multidisciplinary project teams, shared data environment, life cycle information management open up prospects for accelerating research and design work through the use of parallel design methods (concurrent engineering (CE)). Parallel design means the simultaneous implementation of both real and future simulated processes of product development and design. All stages of the life cycle of a high-tech machine-building product are considered simultaneously while the design is modified in order to maximize the efficiency of the product at all stages of its life cycle. The efficiency of the life cycle of a high-tech machine-building product can be understood as improving its quality, increasing the speed of the product entering the market, reducing operating costs, etc. The resources necessary for the production, operation, maintenance, and disposal of the product are determined in the process of product design. Problems of later stages of the life cycle are determined on the basis of modeling and are solved as long as they may arise. Changes in the product life cycle cost the cheapest at the design stage, so parallel design concentrates on making changes at this stage. Therefore, parallel design reduces the costs associated with solving these problems compared to the cost of solving them at the stage of operation and maintenance, as well as accelerates the entry of a high-tech machine-building product into the market.

The above results of research into CALS technologies and systems for the transformation and restoration of mechanical engineering allow us to implement the advanced innovations of Industry 4.0 as soon as possible.

5. 2. Results of studying major innovations of Industry 4.0 on their application for transformation and restoration of mechanical engineering

One of the most important achievements of Industry 4.0 is digital twins. In some approaches, it is proposed to create a digital twin of the object or process at the stage of its development, in others – based on filling the profile with data from sensors at the stage of operation [10, 28–30]. Within the framework of this study, an integrated approach is proposed in which a digital twin is created at the first stage of the life cycle of a high-tech machine-building product – identifying and analyzing needs. Next, it is filled with data at all stages of the life cycle.

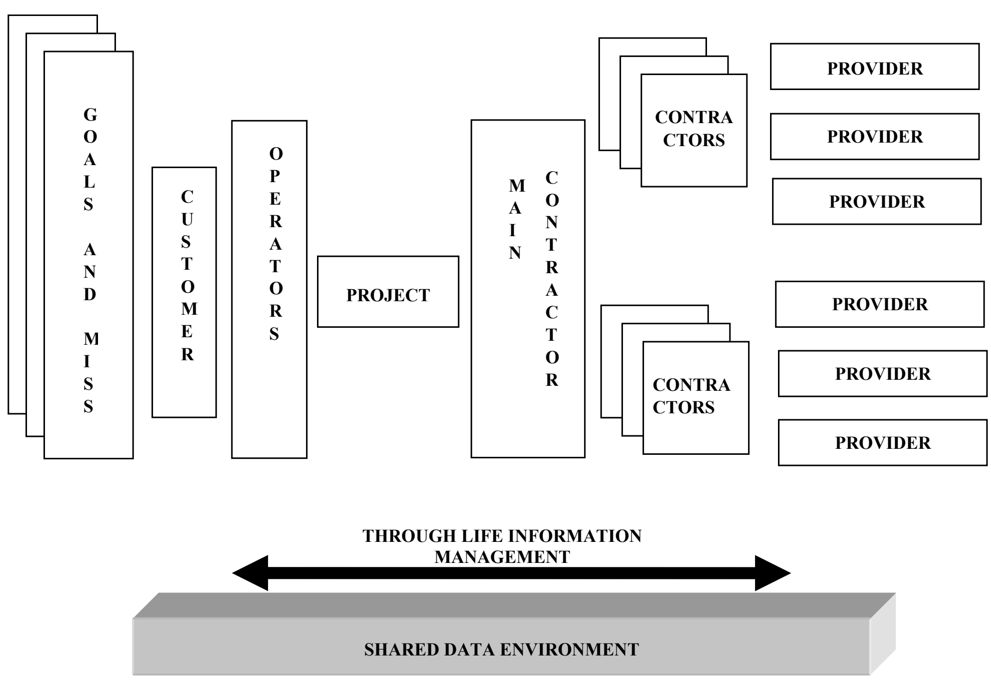

Fig. 1. Infrastructure of participants in the life cycle of high-tech machine-building products, united by a shared data environment

After the disposal of a high-tech machine-building product, it is proposed to use its digital twin to develop more modern similar products. Fig. 2 shows a structural scheme for maintaining the life cycle of high-tech machine-building products using digital twins. Table 1 gives data that should be collected at each stage of the life cycle of high-tech machine-building products to create their digital twins.

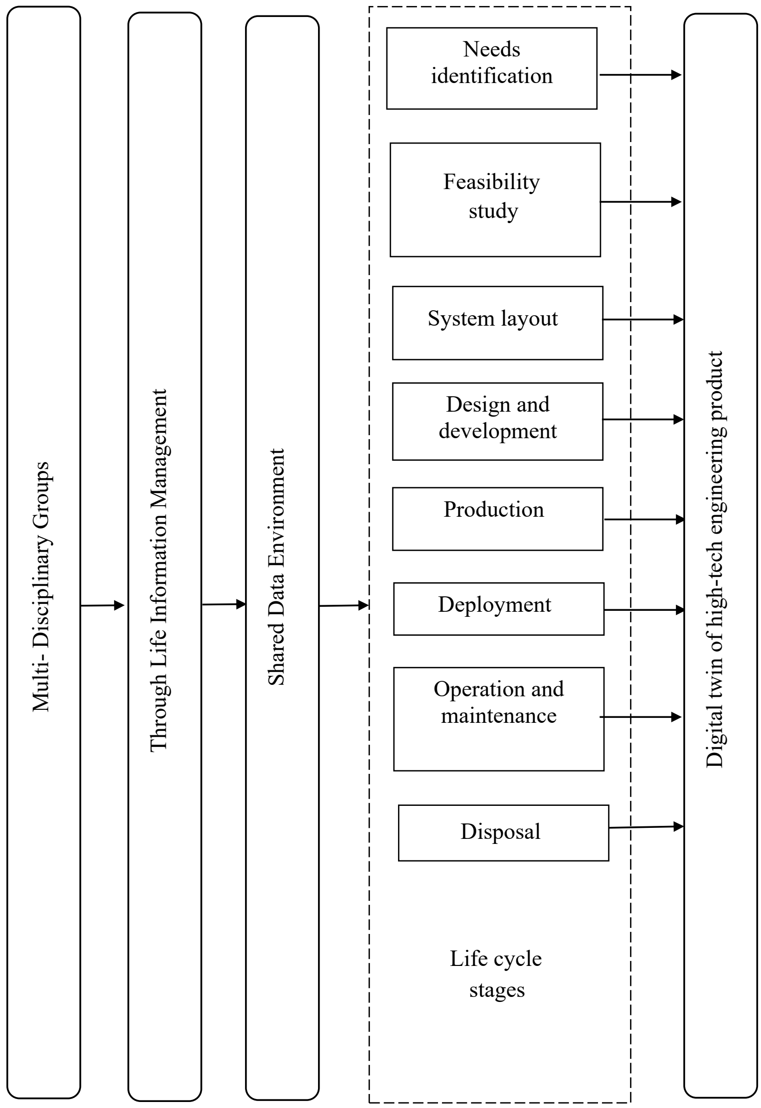

Fig. 2. Structural scheme of maintenance of the life cycle of high-tech machine-building products using digital twins

Table 1

Data to be collected at each stage of the life cycle of high-tech machine-building products

Stage of the life cycle of high-tech machine-building products	Data
Identification and analysis of needs	Quantitative indicators of the desired technical characteristics defined by the customer, according to the purposes and missions
Feasibility study	Quantitative economic indicators are determined on the basis of the desired technical characteristics. Determined by the customer, operator and main contractor.
System layout	Draft documentation developed by the main contractor and contractors
Design and development	Design documentation is developed by the main contractor, contractors and suppliers
Production	Technological documentation is developed by contractors and suppliers
Deployment	Data from contractors and operators on the features of the external environment in which the deployment and operation of high-tech engineering products
Operation and technical support	Data from sensors integrated into a high-tech machine-building product. Product failure data from operators.
Disposal	Data on the degree of wear and the reasons for decommissioning of high-tech machine-building product. This data is collected and entered into the system by the supplier and the operator

The development of digital twins of high-tech machine-building products requires the use of big data technologies and machine learning [31, 32]. Big data can be collected at all stages of the life cycles of high-tech machine-building products [33–35].

The above results are key because they open up opportunities for the introduction of other innovations of Industry 4.0, namely the Internet of Things in engineering, robots, cobots, drones, etc.

5. 3. Results of the synthesis of principles of restoration and transformation of high-tech engineering

The implementation of the main provisions of the CALS concept and innovations of Industry 4.0 on the example of Ukraine is shown in Fig. 1. The flagship of the post-war reconstruction of the machine-building industry of Ukraine should be the defense-industrial complex, which should launch the processes of reconstruction and innovative transformation in civil high-tech engineering. Participants in the life cycle of weapons and military equipment in this case are given in Table 2.

Table 2

Participants of life cycles of weapons and military equipment

Participants in the life cycles of high-tech engineering products	Participants in the life cycles of armaments and military equipment
Setting goals and missions for the development of new and modernization of existing weapons and military equipment	Central Research Institute of the Armed Forces of Ukraine, Central Research Institute of Armaments and Military Equipment of the Armed Forces of Ukraine, State Research Institute of Testing and Certification of Arms and Military Equipment, profile departments of higher military and civilian educational institutions
Customers	Ministry of Defense, Ministry of Internal Affairs, Security Service of Ukraine
Main contractor	State Concern «Ukroboronprom»
Contractors	Enterprises of «Ukroboronprom»
Suppliers	Domestic and foreign enterprises and organizations of various forms of ownership
Operators	Armed Forces of Ukraine, Territorial Defense, Police, National Guard, Security Service of Ukraine

To formalize the process of selecting weapons and military equipment for their primary production, a mathematical model for optimizing the production program (1) has been built. Model (1) takes into consideration the available resources for the SC «Ukroboronprom» and related enterprises.

$$F(x_1, x_2, ..., x_i, ..., x_n) = \\ = c_1 \cdot x_1 + c_2 \cdot x_2 + ... + c_i \cdot x_i + ... + c_n \cdot x_n \to \max,$$

$$\begin{cases} a_{11} \cdot x_1 + a_{12} \cdot x_2 + ... + a_{1i} \cdot x_i + ... + a_{1n} \cdot x_n \le b_1, \\ a_{21} \cdot x_1 + a_{22} \cdot x_2 + ... + a_{2i} \cdot x_i + ... + a_{2n} \cdot x_n \le b_2, \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ a_{j1} \cdot x_1 + a_{j2} \cdot x_2 + ... + a_{ji} \cdot x_i + ... + a_{jn} \cdot x_n \le b_j, \\ \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \\ a_{m1} \cdot x_1 + a_{m2} \cdot x_2 + ... + a_{mi} \cdot x_i + ... + a_{mn} \cdot x_n \le b_m, \\ x_i \ge 0. \end{cases} \quad (1)$$

where:

– x_i is the number of units of military-technical products produced of the ith type;

– c_i is the weight factor for each type of product x_i;

– $F(x_1, x_2, ..., x_n)$ is the objective function that maximizes the number of products produced;

– a_{ji} is the the rate of expenditure of the resource of the j-th type per unit of production of the ith type;

– b_j is the available amount of resource of j-th type.

The number of units of military-technical products produced of the ith type x_i for certain units of products may be fixed at a certain level if these products are critical for improving the defense capability of the state. That is, an additional restriction of the following type is introduced into the model:

$$x_i \ge d_i, \quad (2)$$

where d_i is the minimum required number of products of the first type. There may also be a situation when products of a certain type are unnecessary, for example, if it is supplied by foreign partners. Then for this type of product we introduce restrictions of the type:

$$x_i = 0. \quad (3)$$

The weighting coefficients c_i for each type of product are determined on the basis of expert assessments of the importance of certain types of weapons and military equipment for the security forces of Ukraine.

The constraints of model (1) reflect resource limitations. It can be not only raw materials and components but also human resources, for example, hours of work of skilled workers in scarce specialties, or engineers.

The optimization model (1) is a trivial model of linear programming – a model for optimizing a production program. The peculiarity of the representation of such a model is the need to take into consideration the nonlinearities associated with the optimization of the production program, as well as the stochastic nature of changes in the parameters of the model.

The main of the nonlinearities that will arise at the stage of production of high-tech machine-building products (weapons and military equipment) is the possible dependence of the a_{ji} coefficient on the number of x_i products for certain types of products. This dependence may be caused by the presence of a scale effect. This effect is in reducing or increasing the cost rate of the j-th type resource per unit of production of the i-th type, depending on the volume of production of these products. It is nonlinear in nature and can be represented by a plot, for example, shown in Fig. 3. The plot in Fig. 3 is described by the polynomial dependence of form (4).

$$a_{ij}(x_i) = \beta_1 \cdot x_i + \beta_2 \cdot x_i^2 + \beta_3 \cdot x_i^3 + ... + \beta_k \cdot x_i^k, \quad (4)$$

where $\beta_1, \beta_2, \beta_3, ..., \beta_k$ are the estimates of polynomial coefficients, which are evaluated on the basis of statistical data using regression analysis methods; k is the power of the polynomial.

Using equation (4) in the limitations of optimization model (1) can convert linear constraints into nonlinear constraints of the form:

$$a_{j1} \cdot x_1 + a_{j2} \cdot x_2 + ... + \\ + \begin{pmatrix} \beta_1 \cdot x_i + \beta_2 \cdot x_i^2 + \\ + \beta_3 \cdot x_i^3 + ... + \beta_k \cdot x_i^k \end{pmatrix} \cdot x_i + ... + a_{jn} \cdot x_n \le b_j. \quad (5)$$

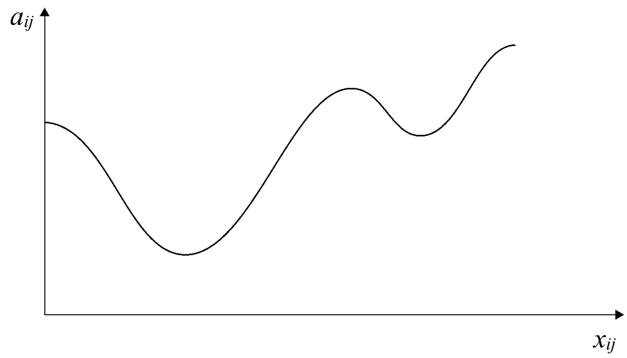

Fig. 3. Possible shape of dependence of the cost rate of a_{ji} resource of j-th type per unit of production of the i-th type on the number x_i of the manufactured products of the i-th type

Thus, we get a more complex, but at the same time more adequate nonlinear optimization model for maximizing the production of weapons and military equipment.

As one can see, the introduction into model (1) of the polynomial regression equation introduces additional stochastic factors into it, in addition to possibly stochastic parameters of the model. The use of stochastic programming models is impractical due to the fact that they can cause difficulties at the stage of practical mathematical modeling. The algorithmic scheme of the approach to the process of optimization of the production program is shown in Fig. 4.

It should be noted that the process of optimizing the production program of the defense-industrial complex is iterative. It has two iterative cycles. A small cycle at the level of a separate contractor (for example, «Ukroboronprom» enterprises and a large cycle at the level of the main contractor. This approach makes it possible to plan the number of weapons and military equipment produced under conditions of uncertainty, and even under the conditions of war. In addition, the advantage of this approach is the ability to use relatively simple mathematical models available for work even to specialists of planned departments of contractors.

Developed for the military-industrial complex, the algorithmic scheme that is shown in Fig. 4 can also be used for civil engineering, for example, during post-war reconstruction. To do this, it is enough only to replace the objects of its use from weapons and military equipment with civilian high-tech machine-building products.

Fig. 5 depicts a possible diagram of priorities in the post-war reconstruction of the military-industrial complex and high-tech engineering specifically.

The top priority is to preserve and reproduce human resources, specifically scientists and engineers who are guided by modern achievements of production informatization and Industry 4.0 principles. The next is data collected throughout the life cycle of high-tech machine-building products, including drawings and technological maps. The third priority is the technological equipment, machine tools, industrial buildings. The fourth is finished products.

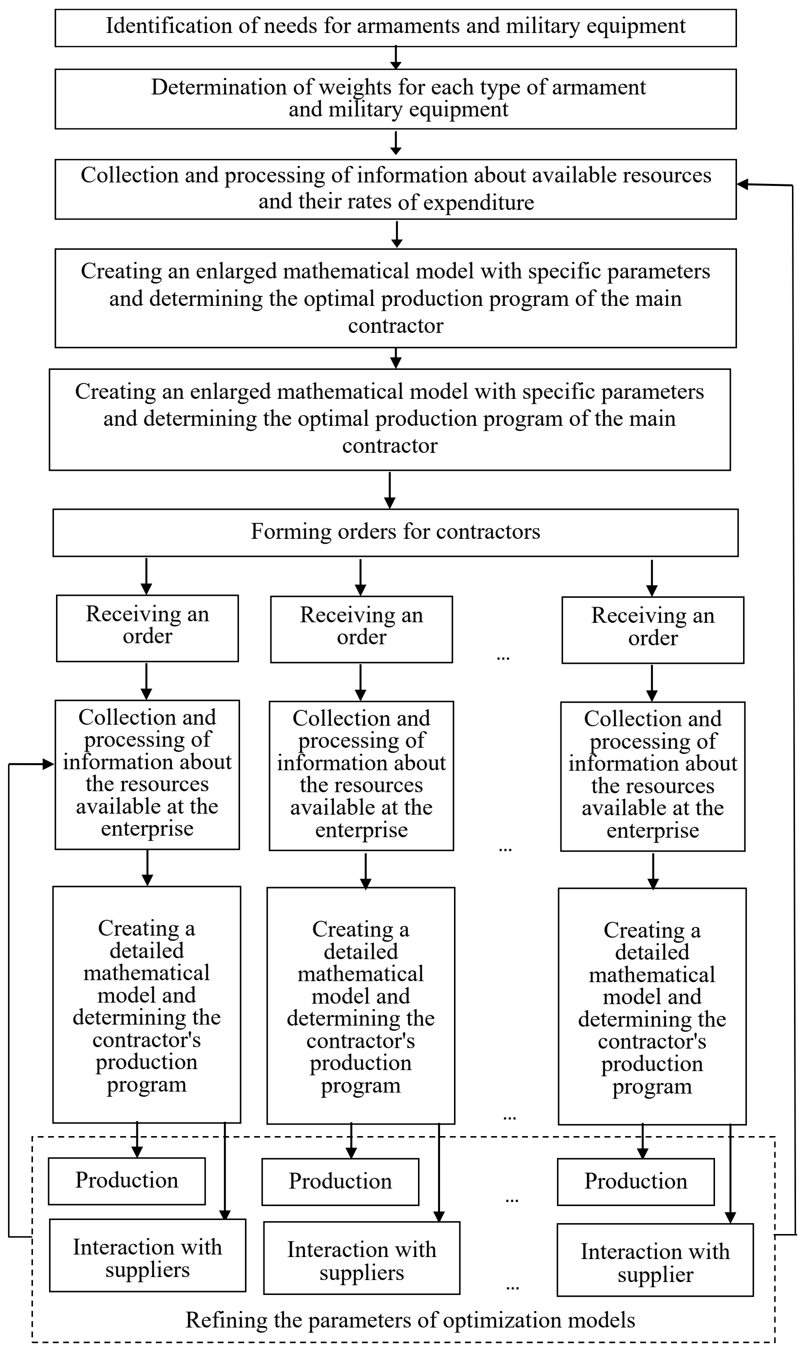

Fig. 4. Algorithmic scheme of optimization of the production program of the defense-industrial complex

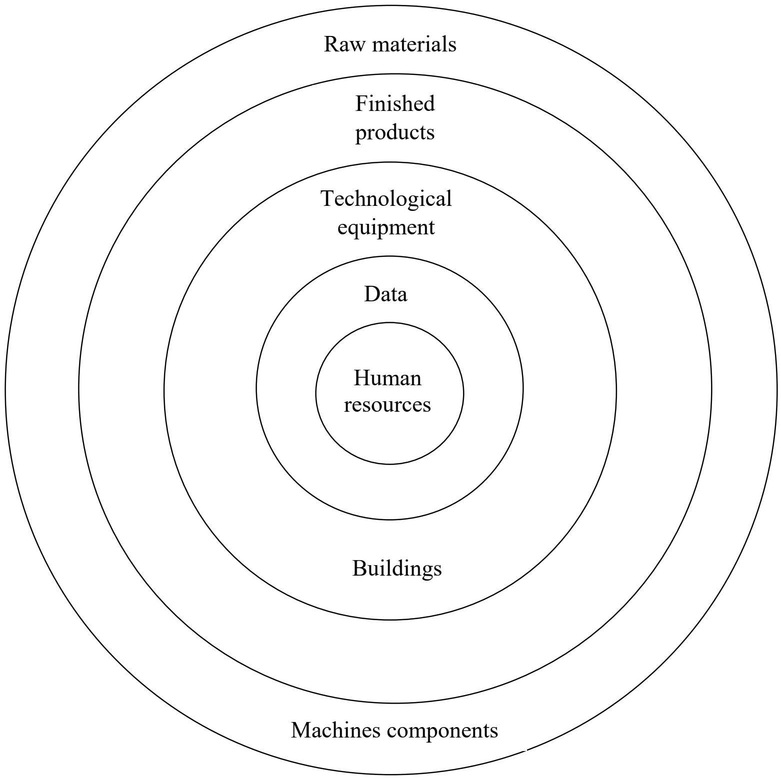

Fig. 5. Priorities of post-war reconstruction of high-tech engineering

6. Discussion of results of studying the principles of restoration and transformation of high-tech engineering

The infrastructure of the participants in the life cycle of high-tech machine-building products (Fig. 1) in combination with the result of systematization of participants in the life cycles of weapons and military equipment (Table 2) makes it possible to accelerate the processes of transformation and restoration of mechanical engineering. First of all, it concerns the defense-industrial complex. The results are achieved through the use of Through Life Information Management and the overall data environment.

An integrated approach, in which the digital twin is filled with data at all stages of the life cycle (Fig. 2) and (Table 1), makes it possible to speed up the process of creating and commissioning new types of equipment. In addition, this approach accelerates the introduction of other innovations of Industry 4.0, namely big data technologies, machine learning, the Internet of Things, robotics. High-tech machine-building products generate a significant amount of data during their life cycles. However, at the Industry 2.0 level, the collection of such data is not systematic. Instead, the proposed comprehensive approach makes it possible to systematize these data. This is achieved through the use of CALS technologies and systems (Fig. 2).

The mathematical model (1) makes it possible to optimize the production program of the military-industrial complex under conditions of uncertainty. This is achieved through the use of an algorithmic scheme for optimizing the production program of the defense-industrial complex (Fig. 4). Thus, the task of restoring the machine-building industry destroyed as a result of hostilities is solved.

Determining the priorities of the post-war reconstruction of high-tech engineering (Fig. 5) will make it possible to concentrate on the most important resources in the process of reconstruction and transformation of high-tech engineering.

Among the main limitations that should be noted is the lack of awareness of the scientific and technical community in the field of CALS technologies and systems and innovations of Industry 4.0. These restrictions can be overcome through seminars, conferences, etc.

The main disadvantage of this study is that it does not contain examples of practical verification of the proposed scientific provisions. This will definitely need to be done in the following studies. Theoretical scientific provisions set out in this paper must be adjusted based on the results of their practical implementation.

The development of Ukrainian high-tech engineering by creating unified elements of a dual-purpose modular design – electric motors, mechanical gears, hydraulic and electrohydraulic drives, etc. is promising. Therefore, it is promising to create modular digital twins of the element base, followed by its integration into the digital twin of the final product. As a pilot project, the creation of digital twins of electrohydraulic mechatronic modules is promising here. This is justified by two reasons, namely:

– the possibility of detailed mathematical modeling of their functional processes based on nonlinear differential equations;

– the ease of obtaining information about working processes of electrohydraulic mechatronic modules at the stage of their testing and operation using modern integrated pressure sensors.

7. Conclusions

1. The introduction of CALS technology and systems in countries with a low pace of implementation of the main innovations of Industry 4.0 should accelerate the passage of the fourth industrial revolution in these countries. The restoration of high-tech engineering, in countries affected by hostilities, is also advisable to carry out using the CALS concept. Among the top priorities for the implementation of CALS technologies and systems are Multi-Disciplinary Groups or Integrated Project Teams, Shared Data Environment, NATO CALS Data Model, Through Life Information Management, Concurrent Engineering. The proposed infrastructure of participants in the life cycle of high-tech machine-building products opens up opportunities for the beginning of the process of transformation of high-tech engineering even before the end of hostilities. This is achieved through the integration of all lifecycle participants through Shared Data Environment and Through Life Information Management.

2. The data that generate a sample of high-tech machine-building products were considered a resource no less valuable than the product itself 10 years ago. However, now, with the advent of the Internet of Things, machine learning and digital twins, the value of data has increased significantly. Specifically, they can be used to optimize maintenance and repair processes, modernize and develop new similar products. The analysis of the main innovations of Industry 4.0 for their application in the transformation and restoration of mechani-

cal engineering showed the possibility of jumping from the level of Industry 2.0 to the level of Industry 4.0. This is especially true for countries in which mechanical engineering has suffered greatly as a result of hostilities. Such a leap can be achieved through the use of CALS technologies and systems to promote the creation of digital twins. Digital twins of high-tech machine-building products, in turn, will simplify the introduction of other innovations of Industry 4.0.

3. The specific filling of the infrastructure of the participants in the life cycle of high-tech machine-building products makes it possible to clearly distinguish the functions of each participant. This ensures the speedy transformation and restoration of high-tech engineering. The mathematical model of optimization of the production program of the defense-industrial complex (on the example of the SC «Ukroboronprom») makes it possible to optimally manage the resources of the machine-building industry even under the conditions of war. These priorities for the restoration of high-tech engineering will make the process of optimizing the production program more certain.

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