DEVELOPMENT OF AN ARCHITECTURAL-LOGICAL MODEL TO AUTOMATE THE MANAGEMENT OF THE PROCESS OF CREATING COMPLEX CYBER-PHYSICAL INDUSTRIAL SYSTEMS

Modern highly technological production puts forward new requirements and approaches to the implementation of the Industry 4.0 concept. To achieve this, it is necessary to develop a cyber-physical production system that would make it possible to fully take into consideration all the factors of the actual production system. All solutions must pursue the global goal of making the best use of production time and resources, as well as meet the "Lean Production" concept. Existing ISO-95, 5C, and 8C cyber-physical production systems (CPPS) reference architectures cannot provide clearly expressed systematization and detailing. Such systems are a set of general recommendations that show the interaction processes among the physical and cyber-components of CPPS. This paper reports a new approach to the systemic representation of the processes for managing the development of complex cyber-physical production systems in the face of today's threats. We have suggested a systemic representation of automating the process of managing the development of complex CPPS. Modern threats to the cyber-physical and information and communication systems (ICS) have been considered, which underlie CPPS. An architectural-logical model, as well as methods for automating the CPPS development process management, have been developed. This could help build a logical relationship from the initial "target" stage to the process of obtaining "management algorithms" at each level and stage of CPPS development as a symbiosis of physical and cyber-components. The devised CPPS development process management model provides an opportunity to propose a group of mathematical models and methods that logically link all development stages into a single "rigid" hierarchical sequence. This makes it possible to build a single information space with a set of complex CPPS development methodology. The proposed solutions could enable the development of an automated system to manage the process of the development of complex CPPS

Keywords: Industry 4.0, Smart Manufacturing, cyber-physical manufacturing systems, multi-systems, metasystem, physical world, cyber world

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1. Introduction

Modern approaches to the implementation of high-tech production are impossible without the use of the Industry 4.0 concept. One of the key points of its application is the development of digital production, which is the collaboration of the physical and cybernetic world into single information space. This approach provides an opportunity to control and manage production processes in real-time modes. As a result, there is a need to design cyber-physical production systems (CPPS) within the framework of Smart Manufacturing, which is a complex research and development task. The current CPPS design methods provide general and highly aggregated recom-mendations that are difficult to implement in practice. Existing solutions usually do not take into consideration the characteristics inherent in a particular production, in which information is carefully controlled and synchronized between the physical production facility and the cyber computing space. Early on in CPPS design, there is an urgent need for the clear determination of the architecture, design sequences, levels, steps, and the description of interactions among them. Existing solutions are built on basic unified principles that do not make it possible to take into consideration the specificity of CPPS design goals and objectives. These solutions cannot provide the clearly expressed systematization and proper details and are a set of general recommendations that show only the

interaction processes among the physical and cyber components of CPPS. Focusing on these solutions does not allow for end-to-end design. In addition, it is necessary to take into consideration possible cyberattacks on CPPS developed, not only external but also internal attacks on the isolated OT-infrastructure (Operational Technology) based on the malware Stuxnet, NotPetya, Triton (Trisis), and Snake (Ekans). The reconnaissance and boot components of new malware specifically designed for OT equipment use the IT environment and its network connections to gain access to industrial control systems.

Thus, it is a relevant task to investigate the systemic representation of complex CPPS development management processes. The development of a design model that would combine the physical and cybernetic components in a single mathematical and information space could make it possible to devise a set of software solutions to automate all stages of CPPS development management.

2. Literature review and problem statement

Automation of CPPS development management processes within Smart Manufacturing concepts is associated with the task of developing a set of mathematical models and procedures that ensure the synthesis of the physical and cybernetic properties of high-tech products. There is a need to find new approaches to the creation of automation systems that would improve production efficiency by integrating the Industry 4.0 (RAMI 4.0) industrial standards and LP approaches. Papers [1, 2] explore the concept of Industry 4.0, which implies creating rules for the description of information data and technical object parameters in the form of a reference model of the Industry 4.0 (RAMI4.0) architecture. The model describes the lifecycle of a technical object, from the creation, production, and use, to its disposal. The Industry 4.0 component is the result of combining the physical and information worlds and the technology of their communication. A detailed analysis of the RAMI 4.0 reference model, which includes all elements of the vertical and horizontal architecture within the Industry 4.0 concept, has revealed the following shortcomings:

– there is no mathematical apparatus to determine how the individual elements within each layer are connected to each other and to the elements that are in the layers above and below a given one.

– the RAMI 4.0 reference architectural model does not describe the "Field Device" and "Product" layers, does not identify the elements and types of connections between them, their interactions with the elements at the "Control Device" layer. As a result, the process of managing the development of CPPS within the framework of Smart Manufacturing on the basis of the architectural model RAMI 4.0 is declarative and does not define specific solutions and sequences of actions in the form of models and methods, the sequence of the process of management of the development of CPPS depending on the goals, the customer's requirements, the equipment fleet of the sites, the workshops at an enterprise, etc. This limitation can be graphically represented in the form of the so-called projection model of the design process control, shown in Fig. 1.

Work [3] lists unresolved problems in the development of production cyber-physical systems in terms of the integrated data collection and analysis. The authors consider the importance of these tasks, as well as their impact on the results of the creation of cyber-physical production systems, which would achieve the implementation of the principles of LP.

It is noted in [4, 5] that constant changes in production systems and product requirements depend on customer requirements, which can be interpreted as an ever-changing goal. This necessitates the development and implementation of cyber-physical production systems that use the principles of the state, self-awareness, and reconfigurability monitoring. However, they are not implemented in any CPPS architectural model, which should have adaptive properties.

The authors of [6, 7] note that for industrial applicability, cyber-physical production systems must meet stringent real-time operating requirements. In doing so, they must provide cost-effectiveness and user-friendliness, using the principles of the Human-Machine Interface (HMI). However, the authors do not offer a specific solution. A flexible HMI cyber-component interface must be developed, depending on the parameters that are generated in real time on a physical level and exert an impact at the SCADA, MES, and ERP levels.

The issues and challenges of CPPS application are addressed in [8]. The increasing complexity of production systems requires appropriate management architectures that provide flexible adaptation during their operation. The authors propose a concept that takes into consideration the complexity and flexibility of CPPS development. However, there are no solutions to achieve the practical implementation of CPPS, which requires a systematic methodology for collecting, processing, and applying data. This necessitates more detailed and systematic research to better apply the required design technologies using a cyber-physical model that could serve as the core for CPPS design in the various production sectors.

Work [9] proposes an adapted structural model of SPPS, which is completely heterarchical. This means that all elements are in a variety of equivalent relationships, and, therefore, there is no prevailing way of structuring them. However, any heterarchy structure is perceived by the developer as incomplete, so it is not acceptable to solve CPPS design tasks in accordance with the concepts of the main purpose and requirements of the technical task. The proposed structural model dismantles links, rather than the sequence and design rules of CPPS.

Paper [10] offers a five-tiered CPPS 5C architecture that contains the levels of "Smart Connection," "Data-to-Information Conversion," "Cyber," "Cognition", and "Configuration". However, the cited paper does not address modern cyber threats to IT- and OT infrastructures taking into consideration their synergy and hybridity. Study [11] offers the architecture of CPPS 8C by adding 3C faces to the 5C architecture. The author emphasizes the horizontal integration of CPPS as the integration of different parties and the associated information component (content). The 5C architecture models proposed in [10], as well as 8C, developed in [11, 12], represent a general design concept and paradigm of these systems. They provide design recommendations but do not offer specific solutions to the structure of the levels and stages of the design and the starting point for CPPS development.
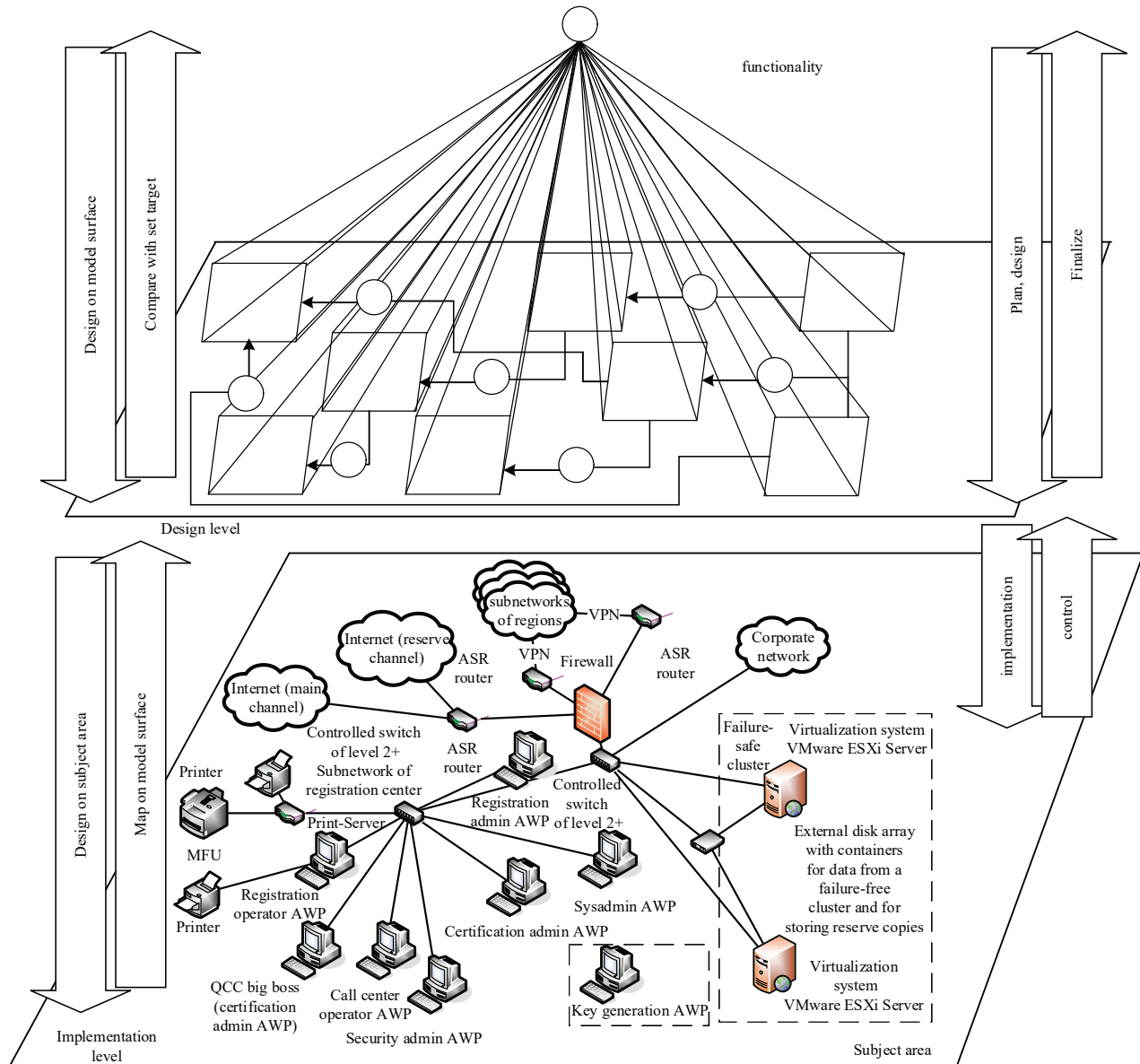
Fig. 1. Projection model of managing the design process

Researchers in [13] emphasize that design patterns should be used to implement cyber-physical production systems. This could help developers build their software using common solutions for mechatronic systems (physical world) and software objects (cyber part) to manage production. However, the authors do not take into consideration that existing CPPS are developed for a certain type of production, for the particular process, CNC machines, sensors, etc. This limits, and most often does not allow the use of design patterns, since the goal, tasks, and requirements of the customer for the developed CPPS at different enterprises can be diametrically opposed.

Our analysis of the scientific literature addressing the topic of the current study has revealed that existing solutions have a verbally descriptive and recommendation character based on a reference architecture, which does not clearly define the sequence of the CPPS development management process and does not offer a mathematical basis for solving automation problems. All this demonstrates the relevance of the purpose and objectives of our research.

3. The aim and objectives of the study

The aim of this study is to develop an architectural and logical model to automate the process of managing the development of complex CPPS.

To accomplish the aim, the following tasks have been set:
– to devise basic concepts of describing an architectural and logical model based on the theories of large systems;
– to build a model of the management process of the development of complex CPPS, taking into consideration both physical and cyber components;
– to develop decision-making methods at the levels of the physical and cybernetic components within the single mathematical information field of CPPS.

4. Research materials and methods

In work [14], the structural-functional model of a self-organizing system, which makes it possible to formalize the

management process and perform mathematical modeling, is shown in Fig. 2.

Here, S is a self-organizing network; UOP is the unit of the original program; USS is the unit of structural self-organization; UFS is the unit of functional self-organization; UPK is the unit of parametric self-organization; UG is the unit of goals; UCC is the unit of criteria calculation; MU is the memory unit; CU is the control unit.

In this case, the proposed model is a model, first of all, of the organizational and technological structure. However, for it to function at the current rate of development of computing resources, and given the growth (modification) of cyberthreats seeking to be integrated with social engineering methods, it is necessary to consider the possible scenarios of their impact on the internal OT-infrastructure of CPPS. Paper [15] proposes using the following classification of cyberthreats to the cyber-physical and information-switching systems, which are the basis of CPPS, shown in Fig. 3.

An analysis of Fig. 3 makes it possible initially, at the design stage, to lay down security profiles against cyberthreats to both IT- and OT CPPS infrastructure. This approach ensures the formation of an information security management system in the early stages, taking into consideration the

synergy and hybridity of modern threats integrated into the methods of software engineering.
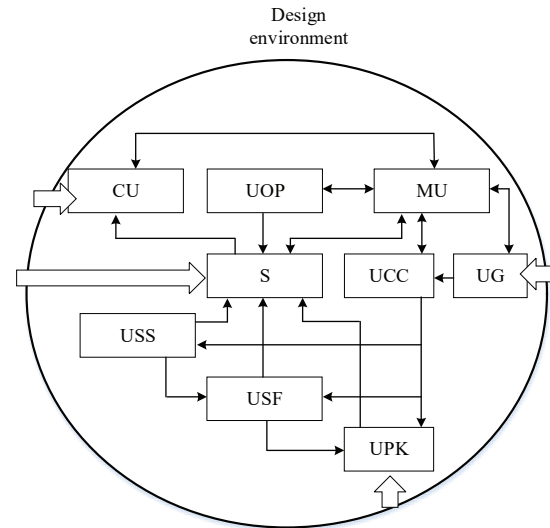

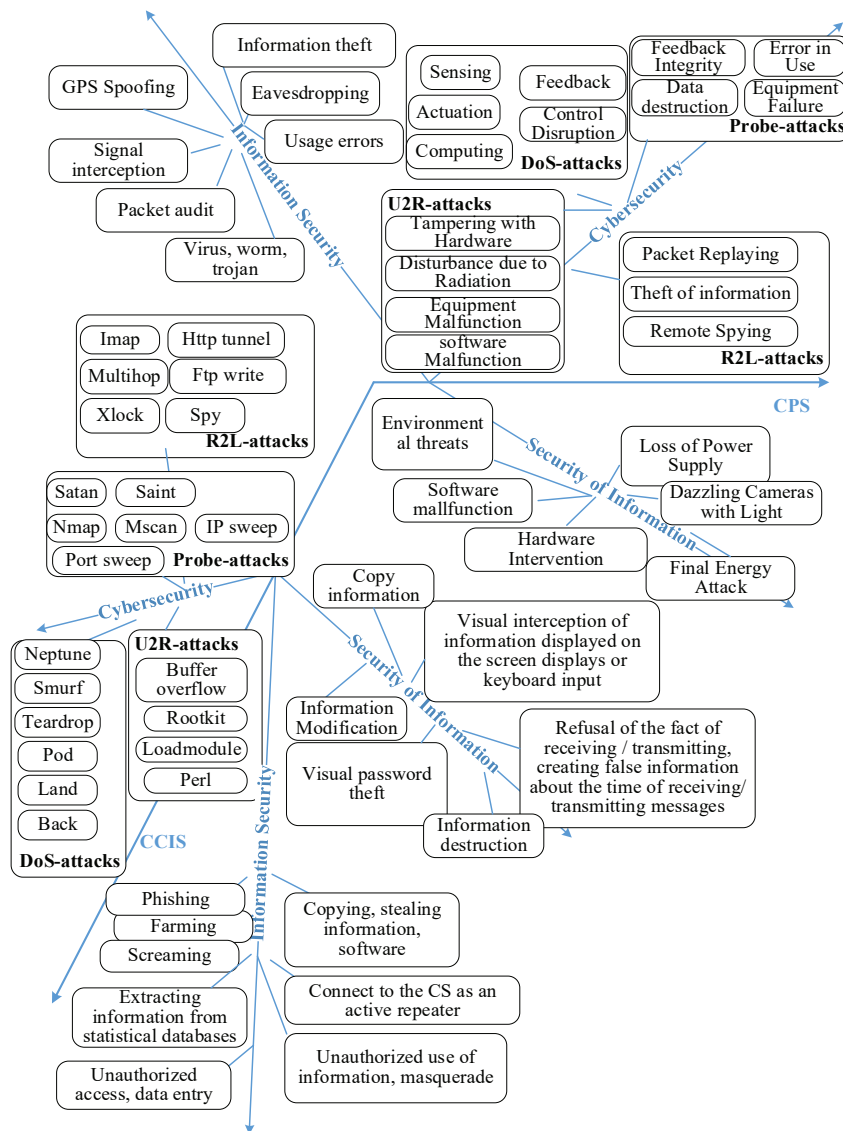Fig. 2. The structural-functional model of a self-organizing system

Fig. 3. A structural scheme of the synergistic model of threats the synthesis on CPPS

5. Developing basic concepts for the description of an architectural-logical model

The model is a reflection of a complex set of logically related methods of design decision-making. Solving the task of constructing an architectural-logical model of the CPPS management process is based on the use of the following concepts: "tree," "level of decomposition," "base." It can be argued that CPPS is a structure of the design solution methods distributed at the "level of decomposition" and "basics", while the "tree" is a tree-like hierarchical structure of the "decomposition levels." Since CPPS is a complex *n*-level object within the technology of Industry 4.0, it is suggested that we start using the decomposition method as the primary method of system analysis. The decomposition method will make it possible to split CPPS into the components based on classification properties or attributes, which will make it possible to determine the levels of hierarchy and form a systemic representation of CPPS. One of the key points of the CPPS multi-level decomposition is the identification and selection of its properties, which are determined by the purpose and objectives of the design. This approach has a significant impact on all stages of CPPS design as it determines not only the structure but also the "tree" of the system. It is proposed to use a targeted decomposition in the early stages of CPPS design, which is to conduct system analysis and tasks in the first step of CPPS design. The results will make it possible to form a set of significant attributes and properties, which in the subsequent stages will allow the decomposition of sub-targets of the underlying levels.

These attributes and properties can be obtained by analyzing existing CPPS, close in purpose and aims, and the new projected CPPS. Such a hierarchical decomposition will make it possible to determine the functional and structural basis, as well as the CPPS algorithm that follows from the design goals and objectives. Therefore, design goals and objectives are dominant because they concentrate all other properties of the projected CPPS.

Based on the basic principles of the theory of large systems ("feedback principle," "compatibility principle" and "law of hierarchical compensation"), the following concepts were introduced into this study:

– the atomic element of the system ($AEofS_i$). This is the indivisible most elementary part of the system, not consisting of any parts, where $i=0...n$. It is worth noting that the atomic elements of the system can have both the same and different properties that characterize their physical or informational nature. Hence, one can write down a condition that at the lowest elementary level CPPS will consist of the set $AEofS_i$. As a result, the following entry $AEofS_i \in CPPS$ becomes valid. The lower level will be defined as the "level of the first level decomposition" of CPPS. Hence, the CPPS representation through the first-level elements can be described in the form of $CPPS = \cup AEofS_i$ at $i=1...n$;

– the ($G\{AEofS\}$) group. These are the combined atomic elements of the system ($AEofS_i$) on the principle of possessing the same properties at the atomic level. The introduction of ($G\{AEofS\}$) will make it possible to represent CPPS through ($G\{AEofS\}$), and, therefore, allow it to describe in the form $CPPS \subset G\{AEofS\}_j$ where $j=1...m$, which corresponds to the second level of complexity of the CPPS representation and is defined as the decomposition of the second level;

– the (Sub_S) subsystem. It is a representation of CPPS on the set ($G\{AEofS\}$) that are grouped and have inherent natural properties. Then the CPPS representation based on the subsystem will make it possible to determine the third level of the decomposition of the object $CPPS \subset Sub\_S_k$ where $k=0...d$;

– the (MS'') multi-system. A combination (Sub_S) of the complex objects that have characteristic properties that make it possible to define an object as the result of the fourth level of the CPPS representation decomposition; it, therefore, can be described by the following expression $MS'' \subset Sub\_S_k$;

– the (MS') metasystem. A combination MS'' based on characteristic properties in accordance with the described logic.

Using the proposed concepts of CPPS representation through decomposition levels and design depth makes it possible to decompose it to the fourth level as a mono system, at the fourth level – as a multi-system, and from the fifth level – as a metasystem with an infinite number of ranks.

6. Developing a model of the complex CPPS development management process

CPPS is a complex "rigidly" hierarchical object that combines both physical and cyber-type processes. Research into the development of such systems within Industry 4.0 can generally be grouped based on design solutions related to the following classes.

General (target):
– management goals;
– management functions.

Cyber-component:
– infologic structure;
– control algorithms;
– information structure (PLM, MES, ERP);
– software (SAD/CAM/CAE);
– software (software and hardware) tools of the integrated information protection system (IIPS).

Physical component:
– management functions;
– organizational and technical structure;
– a set of technical means (PLC, sensors, technological and production equipment, networks, etc.);
– IIPS hardware.

The CPPS development management process is based on two basic approaches to each design solution:
– the synthesis of target, functional, structural, information, and algorithmic solutions, which is an approach to the choice of a specific solution;
– the analysis of each design decision on quality, content, and modeling methods.

To categorize design decisions based on certain properties, it is proposed to use a stratification method that will achieve the goal of developing CPPS. A given method includes a specific set of design solutions for different properties of the object. On this basis, it is proposed to use methods of system analysis of design solutions for the development of CPPS to determine the properties of the object.

Since the design of modern CPPS can take place in both synchronous and asynchronous time mode, a rigid sequence of project decisions must be established. Failure to do so

leads to a change in timing and a higher cost of designing and implementing CPPS at an enterprise.

The design of modern cyber-physical systems is based on targeted control algorithms and information flows of the interaction of structural elements of the object of control, depending on their nature and physical properties. This sequence of design solutions shows that each of them is strictly dependent on the previous one and there is a "rigid" logical sequence of all design decisions in the development of a particular CPPS.

Given this, the following hierarchy of design solutions has been proposed for CPPS:
– target;
– functional;
– organizational-technical;
– infological;
– informational;

– algorithmic (functioning algorithms);
– model (physical modeling and simulation of elementary tasks);
– mathematical (mathematical description of elementary tasks).

The systemic representation of all the control sequence parameters in the development of complex CPPS is shown as an architectural-logical model of automation of the complex CPPS development management process (Fig. 4, *a*, *b*).

Fig. 4 shows that the systemic representation of the automation of the complex CPPS development management process is a hierarchical system with rigid logical connections. The proposed model is a build tree, which makes it possible to form a mathematical description in the form of models and methods of processes for managing the development of complex CPPS, which will make it possible to automate its development.
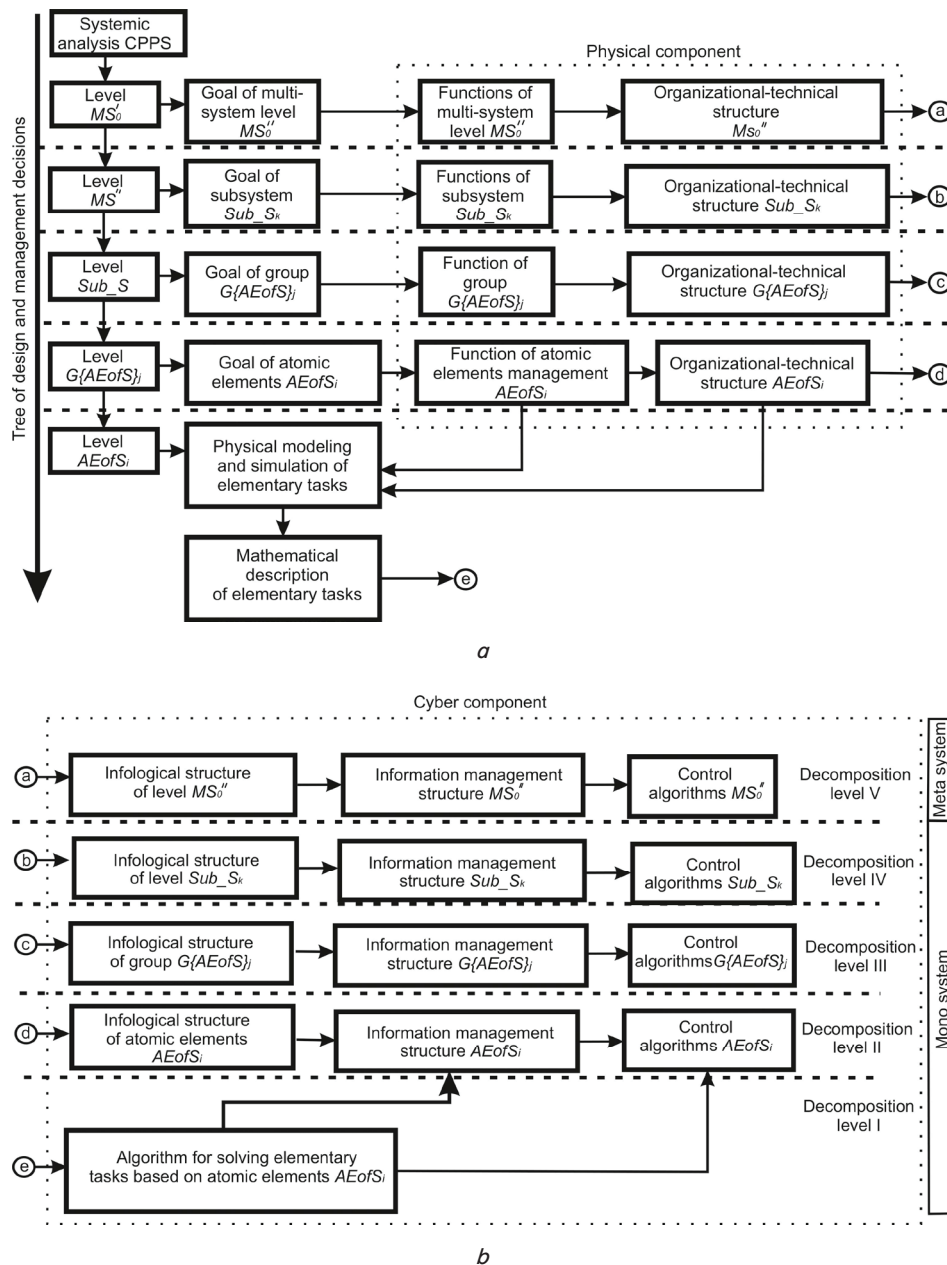

a

b

Fig. 4. Architectural-logical model of automation of the process of managing the development of complex CPPS:
a – physical component; *b* – cyber component

7. Decision-making method at the levels of the physical and cybernetic components of CPPS

Within this study framework, a method has been proposed for making design decisions at a functional level, which implies the following:

– the level of decomposition at the atomic level ($AEofS$) is fixed;

– the means to achieve the goal of the physical component of CPPS are determined;

– the task or group of tasks are determined that are necessary to achieve the set goal.

The starting point for the formal representation of the proposed method is the assumption that the design task or task group is consistent with a design goal. Solving the set of tasks should ensure that the goal is met with efficiency requirements in mind and, if necessary, given the redundancy of the method base. Given this, the correspondence between goals (Aim_i) and tasks ($Task_j$) can be represented in the form of binary ratios:

$$Aim_i \cong Task_j. \tag{1}$$

If there are several Aim_i or $Task_j$, the binary ratios can be represented as follows:

$$Aim_i \cong \Omega_{j=1}^{n} Task_j, \text{ where } j = 1 \ldots n. \tag{2}$$

For each quantitative parameter of the goal $QandQIR$, the atomic elements $AEofS_i$ are selected; the task ($PCofT$) tactical and technical characteristics are calculated. The task characteristics should be fully in line with the objectives set, given that the search for solutions must be tailored to the specificity of the field of science whose phenomena of the subject area are the object of the description and modeling;

– the CPPS system graph functional model is built, taking into consideration the following principles. The graph nodes correspond to the sequence of tasks being developed ($Task_j$), and the connection between the tops of the graph $Task_j$, corresponding to Aim_i, is displayed as the graph's edges. As a result of building a functional model's graph, the developer receives a directed functional graph to achieve the goal by solving a set of relevant tasks $FGofTask_j$. The proposed solution is necessary to control the correctness of design solutions development at the functional stage of the design level used;

– test the set of tasks $Task_j$, required to achieve all set goals Aim_i, for the functional completeness. For this purpose, it is proposed to compare the graphs of the assigned level of design and the tasks of this level. It can be argued that the target graph for MS_0'' (Aim_MS'') is the "parent" of the task graph for MS_0'' ($Task\_MS_0''$) which makes it possible to state the homomorphism of the graphs Aim_MS_0'' and $Task\_MS_0''$;

– the systemic functional graph is marked with parameters $PCofI\_MS_0''$ that are calculated by the developers. This allows for a systemic simulation of the decomposition process $PCofI\_MS_0''$ and a test for compliance with the tactical and technical requirements of the target $QandQIR\_MS_0'$ based on the performance criteria and specific parameters of a given MS_0'.

If the $PCofI\_MS_0''$ modeling results fully meet the assigned requirements $QandQIR\_MS_0''$ and the main goal MS_0', one can consider the design solutions obtained at the functional stage of the system level of design to be correct.

Based on the set of methods proposed, decision-making at the organizational and technical stage can be represented in the form of binary relations as follows:

$$Task_j\_MS_0'' \cong Pattern\_MS_0''. \tag{3}$$

In accordance with the proposed architectural-logical model (Fig. 1), next one needs to develop a decision-making method for the cyber component of CPPS in the later stages of development management: infological, information, and algorithmic. The basic ratios underlying the functioning algorithms at each level take the following form:

– for level MS_0''

$$AF\_MS_0'' = f \begin{pmatrix} Task_j\_MS_0'', StrE\_MS_0'', \\ InputCanal\_MS_0'', \\ OutCanal\_MS_0'', t \end{pmatrix}; \tag{4}$$

– for achieving the goal at level MS_0''

$$AF\_Aim_i\_MS_0'' = f\left(Aim_i\_Sub\_S_k, t\right); \tag{5}$$

– for the goal of subsystem Sub_S_k

$$AF\_Aim_i\_Sub\_S_k = f\left(Task_j\_Sub\_S_k, t\right); \tag{6}$$

– for the subsystem model of level Sub_S_k

$$AF\_Patten\_Sub\_S_k = f\left(Patten\_Sub\_S_k, t\right); \tag{7}$$

– for the infological model $AF\_InputCanal\_Sub\_S_k$

$$AF\_InputCanal\_Sub\_S_k = \\ f\begin{pmatrix} InputCanal\_G\{AEofS\}_j, \\ PCofI\_InputCanal\_G\{AEofS\}_j, t \end{pmatrix}; \tag{8}$$

– for the infological model $AF\_OutCanal\_Sub\_S_k$

$$AF\_OutCanal\_Sub\_S_k = \\ f\begin{pmatrix} OutCanal\_G\{AEofS\}_j, \\ PCofI\_OutCanal\_G\{AEofS\}_j, t \end{pmatrix}; \tag{9}$$

where AF_MS_0'' – functioning algorithm of the subsystem of level MS_0''; $Aim_i\_Sub\_S_k$ – achieving a goal of the subsystem of level Sub_S_k; $StrE\_Sub\_S_k$ – structural elements of level Sub_S_k; $OutCanal\_Sub\_S_k$ – output channels of level Sub_S_k; $InputCanal\_Sub\_S_k$ – input channels of level Sub_S_k; t – time.

In the last phase of design, the CPPS developer builds a MS_0'' subsystem-level operating algorithm. The formal notation of the dependence underlying this algorithm takes the following form:

$$AF\_MS_0'' = f \begin{pmatrix} Aim_i\_Sub\_S_k, StrE\_Sub\_S_k, \\ OutCanal\_Sub\_S_k, \\ InputCanal\_Sub\_S_k, t \end{pmatrix}. \tag{10}$$

Once the AF_MS_0'' algorithm is built, it is mandatory to analyze the fundamental attainability of the relevant goal,

as well as perform simulations taking into consideration the space-time characteristics and the criteria of effectiveness of the process of achieving the goal $Aim_i \_ MS''_o$.

8. Discussion of results of developing an architectural-logical model of CPPS and the proposed method within a single mathematical information field

Our analysis of the scientific literature and existing architectural design solutions of CPPS has revealed a series of shortcomings that indicate that it is impossible to develop a single mathematical representation of CPPS. Attempts to form such a representation are purely advisory at every level of design.

As a result of our research, an architectural-logical model of the process of managing the development of complex CPPS has been developed. A mathematical notation of the systemic representation of automating the complex CPPS development management process, which is based on the theory of large systems (metasystems and mono systems), as well as synthesis and analysis methods, has also been proposed. In addition, the mathematical model takes into consideration modern threats, their integration with social engineering methods, their hybridity, and synergies. This provides an opportunity to combine the physical and cybernetic components into a single information interconnected environment, to form SIM in the initial stages, and to provide preventive measures to counter threats to both IT- and OT CPPS infrastructure. The proposed method could be used to manage the design of complex CPPS, which would simplify the development process, from the initial design level to obtaining CPPS operating algorithms.

During the goal analysis phase, we suggest using the top-down method, while the bottom-up method is to be used in the physical and cybernetic stages. The concepts proposed in this paper, fixed at the appropriate levels of CPPS design and analysis decomposition, make it possible to build a vertical frame of decompositions at all levels of CPPS design in accordance with the intended goal.

Our findings make it possible to systemize and arrange the sequence of actions in the CPPS development management process. A characteristic feature of the proposed architectural-logical model of design is that it is characterized by clearly expressed logical space-time relations, as well as the presence of their mathematical representation. This makes it different from existing CPPS design models. These properties of the model make it possible to form a mathematical representation and provide synthesis within a single mathematical environment sequence of stages in the process of managing the development of complex CPPS and its subsequent automation.

The previously considered architectural design models that currently exist are advisory in nature, do not have a clear logical and mathematical justification and consistency of the stages of CPPS development. However, it is worth noting that the proposed systemic representation of automating the process of managing the development of complex CPPS has the property of a "rigidly" fixed system with clearly formulated logical connections. This reduces its adaptability but makes it possible to develop, based on it, an automation system for managing the development of complex CPPS.

The set of design solutions proposed is not complete in the sense that it does not cover the task to manage the CPPS being developed. To ensure the completeness of the tuples of all the necessary goals and parameters to achieve the design tasks of modern CPPS, it is advisable to represent them as a composition of the following subsystems, mathematical models, and control algorithms:
– a target management system;
– a functional management system;
– an organizational management system;
– an information management system;
– a physical management system;
– a model (mathematical) subsystem;
– an algorithmic control subsystem.

In the future, it is planned to implement a set of decision-making methods at the cyber and physical level based on the developed model, to formalize the systemic models, and to develop a method of synthesis of functioning algorithms. To achieve the goals of automation, it is planned to develop the syntactical and semantic models of the language of definition and description of modeling and implement them as an automated system.

9. Conclusions

1. We have proposed the mathematical concepts to describe complex cyber-physical production systems based on meta- and mono-systems theories. In contrast to existing approaches, the use of the proposed concepts makes it possible to decompose the representation of CPPS to the fourth order as a mono-system, the fourth order – as a multi-system, and, from the fifth order – as a meta-system with an infinite number of ranks. It also makes it possible to synthesize all the stages and levels of CPPS development as a whole.

2. An architectural-logical model has been developed to automate the process of managing the development of complex CPPS. The proposed model, unlike the existing ones, is a "rigid" hierarchical structure of logically interconnected mathematical concepts. The proposed model makes it possible to take into consideration both the physical and cyber components when automating the process of managing the development of complex CPPS and to derive algorithms to operate at each level of management taking into consideration possible cyber threats to the IT- and OT infrastructure of CPPS.

3. A method of design solutions has been proposed, which is based on the developed architectural- logical model. Unlike existing ones, it is an interconnected mathematical sequence of decompositions of the architectural-logical automation model from the initial stage of development (the "main goal" task) to the process of deriving "control algorithms" at each level. This enables to automate the process of managing the development of complex CPPS, reduce design time, and improve cost-effectiveness by introducing CPPS into the manufacturing of high-tech products.

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