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MODEL OF RESOURCE AND QUORUM MANAGEMENT FOR A BLOCKCHAIN-ORIENTED DISTRIBUTED INFORMATION SYSTEM IN A MULTI-CLOUD ENVIRONMENT

The subject of this study is a mathematical model for managing computing resources and ensuring quorum in a blockchain-oriented distributed information system within a multi-cloud environment. **The goal** of the work is to develop a set-theoretic model that formalizes the multi-cloud deployment of components of a blockchain-oriented distributed information system, taking into account its multi-level architecture, the heterogeneity of available resources, the aggregated resource state of nodes, their availability, and the conditions for ensuring quorum during operation under variable load. **Methods**. To achieve the set goal, methods of system analysis were used to formalize the system structure and the connections between its components; methods of mathematical modeling were used to construct a formal description of the multi-cloud environment, the resource state of nodes, control actions, and quorum constraints; statistical analysis methods for processing, aggregating, and normalizing telemetry data; decision-making theory methods for establishing conditions for acceptable resource reallocation; and simulation modeling methods for verifying the performance of the developed model under conditions of variable load, resource scarcity, and variable node availability. **Results.** For the first time, a formalized set-theoretic model has been developed for managing computing resources and ensuring quorum in a blockchain-oriented distributed information system within a multi-cloud environment. Unlike existing approaches, combines, within a single unified representation, the multi-cloud environment as a set of cloud platforms from different vendors, the multi-level system architecture, the aggregated resource state of nodes, the conditions for permissible resource reallocation, and the specified requirements for ensuring quorum. Sets of cloud environments, architectural levels, and system nodes are presented; vectors of available and allocated resources, an aggregated system state vector, a resource deviation function, a quorum assurance function, and a set of permissible control actions are introduced. Simulation studies confirmed the model's operability under nominal operation, resource scarcity, and node availability degradation. This allowed for the formulation of the decision-making process regarding resource reallocation and system operability maintenance within a single mathematical framework. **Conclusions**. The developed model provides a formalized description of the processes of managing computational resources and ensuring quorum in a blockchain-oriented distributed information system in a multi-cloud environment and can be used as a basis for further development of methods for optimizing control decisions and experimental research into the system's operational efficiency under dynamic conditions.

Keywords: mathematical model; resource management; quorum; blockchain; information system; cloud.

1. Introduction

The digital transformation of the financial sector, logistics, healthcare, telecommunications, and other industries is accompanied by the widespread adoption of distributed information systems. Such systems ensure geographically distributed data processing, service availability, scalability of computing power, and operational continuity under varying information flow intensities [1, 2].

One of the directions in the development of distributed information systems is the integration of blockchain technologies into their architecture. The use of blockchain enables data integrity, transparency in transaction recording, increased trust among participants in information exchange, and support for decentralized decision-making procedures [3]. For blockchain-oriented distributed information systems, this is of fundamental importance, since their operability is determined by the availability of individual nodes and the ability to maintain the coordinated functioning of a set of components involved in forming and confirming the system's state [4].

The further development of such systems is linked to the transition to multi-cloud infrastructures [5]. Deploying system components in cloud environments from different vendors allows for reduced dependence on a single vendor, increased scaling flexibility, improved fault tolerance, and load distribution across independent computing platforms [6, 7]. At the same time, multi-cloud deployment complicates system management due to differences in resource allocation models, service characteristics, telemetry data formats, network interaction parameters, and conditions for ensuring node availability [8, 9].

For a blockchain-oriented distributed information system, these complications are of a complex nature. Under such conditions, it is necessary to ensure the rational distribution of computing resources among nodes, services, and deployment environments, as well as to maintain a set of available nodes that preserves quorum and the system's ability to function in a coordinated manner [10, 11]. Given dynamic load changes, partial node degradation, changes in the availability of individual cloud environments, and the heterogeneity of telemetry data, the task of resource management is directly linked to the task of maintaining quorum [11–13].

Approaches to resource management in cloud and distributed systems are primarily focused on service scaling, load balancing, telemetry monitoring, or separate analysis of blockchain interaction mechanisms [14]. At the same time, within the framework of such approaches, the relationship between the resource state of nodes, their availability in a multi-cloud environment, and the conditions for ensuring the quorum of a blockchain-oriented system is not sufficiently formalized. This limits the ability to develop coordinated solutions for resource reallocation in situations where changes to the system configuration affect performance, availability, and the ability to maintain the correct functioning of consensus mechanisms [15–17].

Therefore, the task of developing a mathematical model for managing resources and quorum in a blockchain-oriented distributed information system in a multi-cloud environment is relevant. Such a model must reflect the distribution of system components across cloud environments from different vendors, account for the system's multi-tier architecture, the heterogeneity of computational resources and telemetry metrics, and formalize the conditions under which resource reallocation aligns with requirements for node availability and quorum maintenance. The construction of such a model creates a foundation for the further development of methods for optimizing the management of blockchain-oriented distributed systems in multi-cloud infrastructures.

2. Analysis of current scientific publications and statement of the study problem

The issue of managing computing resources in distributed information systems plays a significant role in current research due to the growing scale of digital services, increasing demands for availability, and the need to ensure the stable operation of systems under fluctuating loads. The integration of blockchain technologies into distributed information systems expands their functional capabilities by ensuring data integrity, transaction transparency, and support for decentralized interaction [18]. At the same time, this complicates resource management processes, since the operability of such systems is determined by the sufficiency of computing power, the composition of available nodes, and the ability to maintain coordinated functioning of components involved in confirming the system's state and executing transactions [19, 20].

The paper [21] examines the architectural aspects of implementing the Blockchain-as-a-Service concept and approaches to deploying blockchain network nodes in a cloud environment. It is shown that delegating part of the infrastructure functions to a cloud provider simplifies the deployment and maintenance of blockchain services. However, the presented approach focuses primarily on the infrastructure organization of the service and does not include a formalized description of coordinated management of node resources and quorum maintenance when system components are deployed across multiple independent cloud environments.

A stochastic approach to scaling is presented in [22], where the Ito equation and the Wiener process are used to describe changes in traffic intensity in real time. The results confirm the feasibility of developing adaptive scaling policies based on predictive load estimates. However, the presented model is focused on a single-cloud environment; therefore, differences between cloud vendors and the conditions for ensuring quorum in a blockchain-oriented distributed information system are not formalized within its framework.

Another approach is presented in [23], where an adaptive approach to managing cloud infrastructure resources based on intelligent load forecasting algorithms is proposed. The authors demonstrate that the use of recurrent neural networks allows for increased efficiency in resource reallocation and reduced operational costs compared to static schemes. The primary focus of this study is on the performance and economic efficiency of cloud services. At the same time, the specifics of blockchain-oriented distributed systems, for which, in addition to resource provisioning, the conditions for node availability and quorum maintenance must be formalized, are partially revealed.

A separate class of approaches is related to the migration of virtual machines and periodic analysis of

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node status. It is precisely this logic that forms the basis of the study [24], which examines resource management in distributed cloud infrastructures under conditions of resource scarcity. The advantage of this approach is the relative simplicity of the mathematical formulation and its practical focus on maintaining service quality metrics. At the same time, it does not address the task of consistently accounting for heterogeneous telemetry data obtained from cloud environments of different vendors, nor does it formalize the impact of changes in the composition of available nodes on maintaining the quorum of a distributed system.

General aspects of the described problem of using blockchain technologies in digital environments and issues of resource provision for complex computing platforms are discussed in [21, 23]. Requirements for the secure operation of distributed platforms are considered in [25]. These results are important for establishing the general context of the research; however, they lack a comprehensive mathematical model that combines the deployment of the system across multiple cloud environments, the multi-level organization of its components, the aggregated resource state of nodes, and formalized conditions for ensuring quorum.

The analysis conducted indicates that existing studies cover individual aspects of building blockchain-oriented systems, service scaling, telemetry monitoring, resource reallocation, and the operation of cloud infrastructures [20, 22–24]. The approaches considered overlook the task of formalizing a unified management model that combines the resource aspect of a blockchain-oriented distributed information system's operation with the conditions for maintaining a quorum in a multi-cloud environment.

An unresolved part of the general problem is the development of a mathematical model for managing the computational resources and quorum of a blockchain-oriented distributed information system, in which the multi-cloud environment is presented as a set of cloud platforms from different vendors, and the system itself is viewed as a multi-level structure of interconnected nodes and services. Such a model must account for the heterogeneity of available resources and telemetry data, dynamic changes in load, changes in node availability, as well as the conditions under which resource reallocation is aligned with the requirements for maintaining the quorum and the stable operation of the system as a whole.

3. Research aim and objectives

The aim of this work is to develop a mathematical model for managing computing resources and the quorum of a blockchain-oriented distributed information system in a multi-cloud environment. The model under development is intended to formalize the representation of a multi-cloud environment as a set of cloud platforms from different vendors, reflect the system's multi-level architecture, establish the relationship between the resource state of nodes, their availability, and the conditions for ensuring quorum, and define formal conditions for the system's transition between states during resource reallocation in the course of operation.

To achieve the stated goal, the following tasks must be solved in this work:

– present a mathematical description of a blockchain-oriented distributed information system in a multi-cloud environment, taking into account the deployment of its components across cloud platforms from different vendors, the heterogeneity of available resources, the multi-level organization of nodes, and dynamic changes in the system's state;

– develop a mathematical description of the process of managing computational resources based on aggregated metrics of the resource system's steady-state operation, resource shortages, and changes in load intensity;

– define formalized conditions for node availability and quorum assurance as constraints that must be adhered to when making decisions regarding resource reallocation to maintain system operability in a multi-cloud environment.

4. Materials and methods of the study

The subject of this study is the processes of managing computing resources and state of nodes, which allows for accounting for the ensuring a quorum of available nodes in a blockchain-oriented distributed information system within a multi-cloud environment.

The subject of the study is a mathematical model for managing computational resources and ensuring quorum in a blockchain-oriented distributed information system in a multi-cloud environment, which takes into account the placement of nodes on cloud platforms from different vendors, the heterogeneity of available resources, aggregated resource state metrics, and dynamic changes in the system's state during its operation.

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The research hypothesis is that the use of a formalized set-theoretic model, which combines an aggregated representation of the resource state of nodes with specified quorum conditions, enables coordinated decisions regarding the redistribution of computational resources and maintains the operability of a blockchain-oriented distributed information system in a multi-cloud environment under conditions of variable load and variable node availability.

To achieve the set goal, the following were used:

– methods of system analysis to formalize the composition of system components, their interrelationships, and the representation of a multi-cloud environment as a set of cloud platforms from different vendors;

– methods of mathematical modeling to construct a formal description of the resource state of nodes, their availability conditions, and quorum constraints;

– statistical analysis methods for processing, aggregating, and normalizing telemetry data;

– decision-making theory methods for formalizing the conditions for resource reallocation as the system state changes;

– simulation modeling methods for verifying the performance of the developed model under variable load conditions and changes in the composition of available nodes.

The information basis of the study is a set of telemetry data received from nodes of a blockchain-oriented distributed information system deployed in a multi-cloud environment. This data includes metrics on CPU time and RAM usage, as well as node availability indicators in each cloud environment. The collected values form a multidimensional time series reflecting changes in the system's resource state at discrete points in time.

For a node $v_{c,\ell,j}$ located in a cloud environment c, belonging to level ℓ of a multi-level architecture, and having index j, the vector of primary metrics at time t is given in the form

$$\bar{\mu}_{c,\ell,j}(t)=\left\{\mu^{\alpha}_{c,\ell,j}(t),\mu^{\beta}_{c,\ell,j}(t),\mu^{\gamma}_{c,\ell,j}(t)\right\}, \qquad (1)$$

where $\mu^{\alpha}_{c,\ell,j}(t)$ – processor time usage metric; $\mu^{\beta}_{c,\ell,j}(t)$ – RAM usage metric; $\mu^{\gamma}_{c,\ell,j}(t)$ – a metric that reflects the node's availability at a given point in time *t*.

To ensure the comparability of heterogeneous metrics (1) obtained from cloud platforms of different vendors, a normalization procedure is applied. The normalized metric value is defined as

$$\hat{\mu}^{\kappa}_{c,\ell,j}(t)=\sqrt{\frac{\mu^{\kappa}_{c,\ell,j}(t)-\mu^{\min}_{\kappa}}{\mu^{\max}_{\kappa}-\mu^{\min}_{\kappa}}},\ \kappa\in K, \qquad (2)$$

where $K=\{\alpha,\beta,\gamma\}$ – a set of metric types; $\mu^{\kappa}_{c,\ell,j}(t)$ – current value of the metric of type κ; $\mu^{\max}_{\kappa}$ and $\mu^{\min}_{\kappa}$ – the minimum and maximum values of the metric of type κ in the system under study.

Normalization (2) ensures that the metrics are scaled to a common scale and increases the model's sensitivity to changes in the resource state of the nodes. The normalized node metrics are used to form an aggregated system state vector at a given point in time t:

$$\bar{S}(t)=\left\{\hat{\mu}^{\kappa}_{c,\ell,j}(t)\ \middle|\ c\in C,\ell\in L, j\in V_{c,\ell},\kappa\in K\right\}. \qquad (3)$$

In formula (3), the set of vectors $\bar{S}(t)$ components reflect the resource status of the nodes in all cloud environments that make up the blockchain-oriented distributed information system.

The simulation study was conducted in two stages. In the first stage, a software model was implemented for the processes of collecting, normalizing, and aggregating telemetry metrics, as well as the decision-making logic for resource reallocation based on changes in the system's state. For this purpose, Python 3.11 and the NumPy and Pandas libraries were used, which enable the processing of multidimensional data arrays and the modeling of discrete system transitions between states.

In the second stage, a virtualized environment built on Oracle VM VirtualBox, Proxmox VE, Docker, and Kubernetes was used to verify the operational capability of the developed model. This configuration made it possible to simulate a multi-cloud environment as a set of isolated computing platforms with different resource provisioning parameters and to generate simulation scenarios of system operation under conditions of variable load, resource shortages, and a variable composition of available nodes.

The effectiveness of the developed model is evaluated based on the results of simulation scenarios, within which changes in the aggregated resource state of nodes, the feasibility of resource reallocation, and the fulfillment of quorum conditions are analyzed. This approach allows us to verify the model's suitability for describing the management processes of a blockchain-oriented distributed information system in a multi-cloud environment.

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5. Research results

5.1. Formalization of multi-cloud component deployment and the system resource model

In this study, a blockchain-oriented distributed information system is viewed as a set of components deployed across multiple cloud environments from different vendors. Control decisions regarding changes in resource allocation and the configuration of active components are generated by a logically isolated element of the control subsystem. A block diagram of this interaction is shown in Fig. 1. Unlike the previous study [26], in which the formalization of metric collection was performed for a single cloud environment, in this work the system model is extended to the case of multi-cloud deployment of components and subsequent decision-making regarding resource reallocation.

A multi-cloud environment is represented as an ordered set of independent cloud platforms

$$C^* = \{C_1, C_2, \ldots, C_M\}, \tag{4}$$

where M – the number of cloud environments in which the components of a blockchain-based distributed information system are deployed.

Each cloud environment C_c, $c = \overline{1, M}$ is characterized by its own vector of available computing resources:

$$\bar{R}_c = \{R_c^{\xi_1}, R_c^{\xi_2}, \ldots, R_c^{\xi_H}\}, \tag{5}$$

where ξ_h, $h = \overline{1, H}$ – type of computing resource.

Further, ξ_1 may refer to processing resources, ξ_2 – RAM, ξ_3 – storage resource, ξ_4 – network resource.

The system architecture is viewed as multi-tiered, although the set of tiers is not identical to the set of cloud environments. For a formal description, let us introduce the set of levels

$$L = \{\ell_1, \ell_2, \ldots, \ell_L\}, \tag{6}$$

where L – number of system architecture levels.

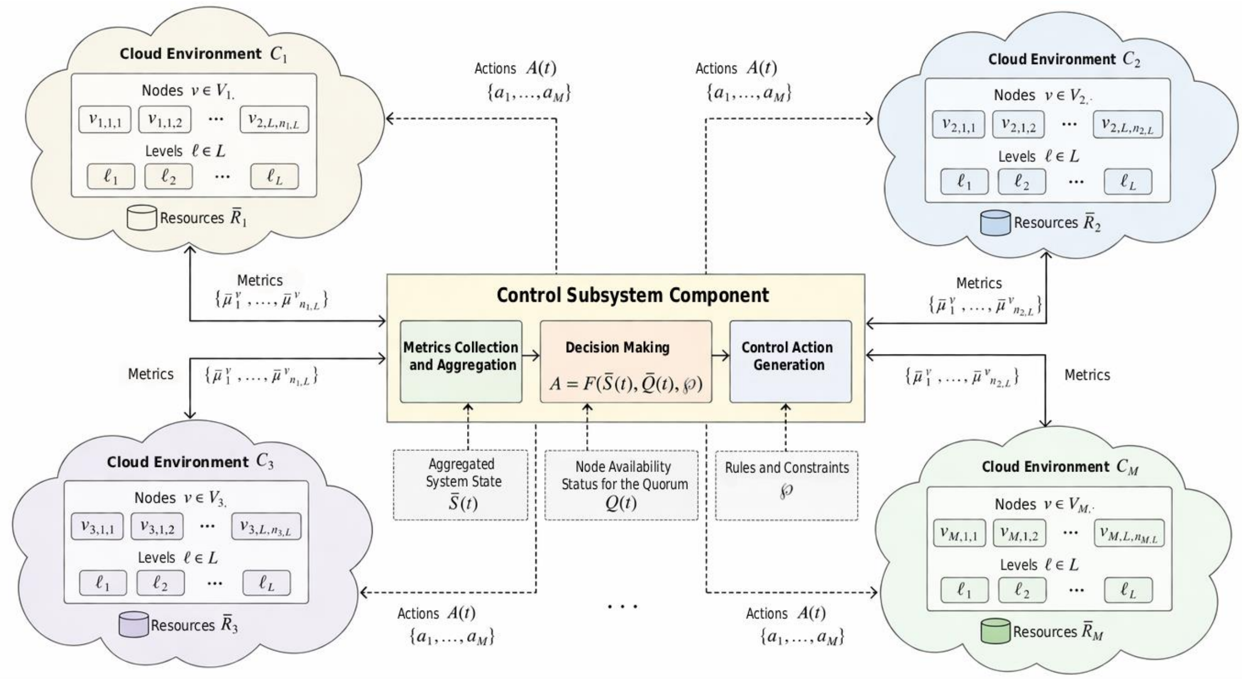

Fig. 1. Block diagram illustrating the interaction between a control subsystem element and the components of a blockchain-based distributed information system in a multi-cloud environment

Depending on the implementation method, the set L may include the infrastructure layer, the virtualization layer, the containerized services layer, the blockchain nodes layer, and the application services layer.

For each pair (C_c, ℓ), where $C_c \in C^*$, $\ell \in L$, let's enter a set of nodes

$$V_{c,\ell} = \{v_{c,\ell,1}, \ldots, v_{c,\ell,N_{c,\ell}}\},\ j = 1, \ldots, N_{c,\ell}, \tag{7}$$

where $N_{c,\ell}$ – number of nodes in the layer ℓ, located in a cloud environment C_c.

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Then the complete set of nodes in the system is defined as:

$$V = \bigcup_{c=1}^{M}\bigcup_{\ell\in L} V_{c,\ell} . \qquad (8)$$

Each node $v_{c,\ell,j} \in V_{c,\ell}$ is associated with a vector of resources allocated for its operation:

$$\bar{r}_{c,\ell,j} = \left\{ r_{c,\ell,j}^{\xi_1}, r_{c,\ell,j}^{\xi_2}, \ldots, r_{c,\ell,j}^{\xi_H} \right\}, \qquad (9)$$

where $r_{c,\ell,j}^{\xi_H}$ – volume of resource type ξ_h, assigned to the node $v_{c,\ell,j}$ in a cloud environment C_c.

In addition to the resources directly allocated to the system's nodes, in every cloud environment, a portion of the resources is used to support platform services, network interaction, system services, and virtualization tools. For a cloud environment C_c, these costs are represented by a vector

$$\bar{S}_c = \left\{ S_c^{\xi_1}, S_c^{\xi_2}, \ldots, S_c^{\xi_H} \right\}. \qquad (10)$$

In that case, the conditions for the acceptable placement of system components within the cloud environment C_c are determined as follows:

$$\sum_{\ell=1}^{L}\sum_{j=1}^{N_{c,\ell}} \bar{r}_{c,\ell,j} + \bar{S}_c \preceq \bar{R}_c , \; c = \overline{1,M} , \qquad (11)$$

where symbol $\preceq$ denotes element-wise comparison of vectors.

Equation (11) specifies the condition under which the total resource consumption for the operation of nodes at all levels and the service infrastructure does not exceed the available resources of the corresponding cloud environment.

The resource state of the system's nodes at a given point in time t is described by normalized metrics aggregated into a vector $\bar{S}(t)$ in accordance with relations (1)–(3). It is this vector $\bar{S}(t)$ that reflects the current state of the set V, taking into account the placement of nodes in different cloud environments and at different architectural levels. In the structure shown in Fig. 1, the control subsystem element receives $\bar{S}(t)$ as a generalized representation of the system's current state, information about node availability, and decision-making rules, based on which it generates control actions to change the distribution of resources and the configuration of active components.

In light of the above, the functioning of an element of the control subsystem at the structural level can be expressed as a formula:

$$A(t) = F\left(\bar{S}(t), \bar{Q}(t), \wp\right), \qquad (12)$$

where $A(t)$ – a generalized representation of a control decision at a given point in time t, which can be specified by a set of control actions; $\bar{Q}(t)$ – a vector representing the availability of nodes relevant to quorum maintenance; $\wp$ – a set of rules and constraints that determine the admissibility of management decisions.

Equation (12) defines the general decision-making framework and serves as the basis for the subsequent formalization of the resource management process and the conditions for ensuring a quorum.

Thus, equations (4)–(12) define the formal basis of the model for the multi-cloud deployment of components in a blockchain-oriented distributed information system. The proposed representation distinguishes between the set of cloud environments C, the set of architectural levels L, the set of nodes V, and the vectors of available and allocated resources, which forms the basis for describing resource reallocation procedures and verifying quorum conditions.

5.2. Mathematical description of the management process for computing resources

The process of managing computational resources can be represented as a sequence of discrete control decisions made by an element of the control subsystem based on the aggregated state vector $\bar{S}(t)$, defined by Equation (3). Within this framework, the control subsystem evaluates the current distribution of resources among nodes at every instant t, determines the need for their adjustment, and generates an admissible control action.

We define the current distribution of computational resources for node $v_{c,\ell,j}$ at time t by the vector

$$\bar{r}_{c,\ell,j}(t) = \left\{ r_{c,\ell,j}^{\xi_1}(t), r_{c,\ell,j}^{\xi_2}(t), \ldots, r_{c,\ell,j}^{\xi_H}(t) \right\}, \qquad (13)$$

In (13), the components of the vector $\bar{r}_{c,\ell,j}(t)$ specify the actual amount of resources of types ξ_h allocated to node $v_{c,\ell,j}$ in the cloud environment C_c at control step t.

It is advisable to determine the node's resource demand at time t based on its metric vector $\bar{\mu}_{c,\ell,j}(t)$ (1), using the formula:

$$\bar{d}_{c,\ell,j}(t) = G_{c,\ell,j}\left(\bar{\mu}_{c,\ell,j}(t)\right), \qquad (14)$$

where $G_{c,\ell,j}(\cdot)$ is a function that transforms the node's metrics into a vector of required resources.

Equation (14) provides an estimate of the number of resources required by the node $v_{c,\ell,j}$ to maintain its operation under the current load conditions. The resource deviation vector is determined based on the difference between the required and actually allocated amounts of resources:

$$\bar{\Delta}_{c,\ell,j}(t)=\bar{d}_{c,\ell,j}(t)-\bar{r}_{c,\ell,j}(t). \quad (15)$$

In equation (15), the positive components of the vector $\bar{\Delta}_{c,\ell,j}(t)$ correspond to a resource deficit, while the negative components correspond to the presence of a reserve.

The control influence on the node $v_{c,\ell,j}$ is represented by the vector

$$\bar{u}_{c,\ell,j}(t)=\left\{u^{\xi_1}_{c,\ell,j}(t),u^{\xi_2}_{c,\ell,j}((t),\ldots,u^{\xi_H}_{c,\ell,j}(t)\right\}. \quad (16)$$

where $\bar{u}_{c,\ell,j}(t)$ is the change in the volume of the resource of type ξ_h , which is performed at control step *t*.

Then, the transition to a new resource allocation is determined by the relation:

$$\bar{r}_{c,\ell,j}(t+1)=\bar{r}_{c,\ell,j}(t)+\bar{u}_{c,\ell,j}(t). \quad (17)$$

Equation (17) defines the dynamics of changes in a node's resource state under the influence of a control decision. The validity of such a decision must be verified at both the cloud environment level and the individual node level.

Constraints on the total amount of resources that can be allocated to nodes within the cloud environment C_c are determined by the condition:

$$\sum_{\ell=1}^{L}\sum_{j=1}^{N_{c,\ell}}\left(\bar{r}_{c,\ell,j}+\bar{u}_{c,\ell,j}\right)+\bar{S}\preceq\bar{R}_c,\ c=\overline{1,M}\ . \quad (18)$$

Condition (18) aligns control actions with the available resources of the corresponding cloud environment and the service costs introduced in formula (10).

For each node, permissible limits for resource allocation are also specified:

$$\bar{r}^{\min}_{c,\ell,j}\preceq\bar{r}_{c,\ell,j}(t+1)\preceq\bar{r}^{\max}_{c,\ell,j}. \quad (19)$$

Equation (19) constrains the new node resource vector with the platform's technical parameters, virtualization parameters, and service configuration limits.

A separate condition for stable node operation is introduced, defined by the interval of permissible resource states

$$\bar{\rho}^{\min}_{c,\ell,j}\preceq\bar{r}_{c,\ell,j}(t+1))\preceq\bar{\rho}^{\max}_{c,\ell,j}. \quad (20)$$

$\bar{\rho}^{\min}_{c,\ell,j}$ $\bar{\rho}^{\max}_{c,\ell,j}$ – the lower and upper bounds of the resource interval for stable node operation, respectively $v_{c,\ell,j}$.

Based on condition (20), it is appropriate to introduce a node stability indicator:

$$\chi_{c,\ell,j}(t+1)=\begin{cases}1, & \bar{\rho}^{\min}_{c,\ell,j}\preceq\bar{r}_{c,\ell,j}(t+1)\preceq\bar{\rho}^{\max}_{c,\ell,j},\\ 0, & otherwise.\end{cases} \quad (21)$$

Equation (21) allows us to transition from a continuous description of the resource state to a logical indicator of a node's operational readiness following the execution of a control action.

To select a control decision regarding resource reallocation, we introduce a quality functional:

$$J_R(t)=\sum_{c=1}^{M}\sum_{\ell=1}^{L}\sum_{j=1}^{N_{c,\ell}}\omega_{c,\ell,j}\left\|\bar{\Delta}_{c,\ell,j}(t)-\bar{u}_{c,\ell,j}(t)\right\|_1, \quad (22)$$

where $\omega_{c,\ell,j}$ is the weight coefficient of node priority $v_{c,\ell,j}$; $\|\cdot\|_1$ is the L_1 is the norm of the vector.

Functional (22) characterizes the total unregulated resource deviation after control actions have been performed. The task of managing computational resources then reduces to selecting a set of vectors $\bar{u}_{c,\ell,j}(t)$ for which functional (22) takes on a minimum value subject to constraints (18)–(21):

$$A^*_R(t)=\arg\min_{A_R(t)}J_R(t), \quad (23)$$

where $A_R(t)=\left\{\bar{u}_{c,\ell,j}(t)\right\}$ is the set of control actions formed at step *t*.

Thus, equations (13)–(23) define the resource component of the mathematical model for controlling a blockchain-oriented distributed information system in a multi-cloud environment. Within this component, the aggregated system state $\bar{S}(t)$, defined by equation (3), is used to assess the nodes' resource requirements, generate control actions, and verify their admissibility under resource constraints.

5.3. Formalized conditions for ensuring quorum and the admissibility of system transitions between states

The resource component of the model defines the rules for generating control actions based on the current aggregated state of the system $\bar{S}(t)$; however, for a blockchain-oriented distributed information system, the validity of a control decision is determined by resource constraints and the preservation of a sufficient number of available nodes to ensure a quorum. To this end, we introduce a formalized description of the set of nodes relevant for maintaining a quorum.

Let:

$$V^q\subseteq V. \quad (24)$$

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In (24), V^q is a subset of the system's nodes whose participation is taken into account when forming a quorum. The set may include validators, transaction confirmation nodes, replication coordinators, or other components upon which the maintenance of the system's consistent state depends.

For each node $v_{c,\ell,j} \in V^q$, let us introduce a quorum availability indicator

$$\eta_{c,\ell,j} = \begin{cases} 1, & \mu^{\gamma}_{c,\ell,j} \geq \theta^{\gamma} \wedge \chi_{c,\ell,j}(t) = 1, \\ 0, & otherwise, \end{cases} \tag{25}$$

where θ^{γ} is the availability threshold.

Equation (25) establishes that a node is taken into account when forming a quorum only if two conditions are met simultaneously: the node is accessible according to its state metric, and its resource state falls within the stable operation interval.

The availability state of nodes relevant to the quorum at time t is given by

$$\bar{Q}(t) = \left\{ \eta_{c,\ell,j}(t) \,\middle|\, v_{c,\ell,j} \in V^q \right\}. \tag{26}$$

Based on the vector $\bar{Q}(t)$ (26), we introduce the quorum assurance functional:

$$\Psi(t) = \sum_{v_{c,\ell,j} \in V^q} \psi_{c,\ell,j} \eta_{c,\ell,j}(t), \tag{27}$$

where $\psi_{c,\ell,j}$ is the weight coefficient of node $v_{c,\ell,j}$ in the quorum formation procedure.

In the simplest case, for equivalent nodes, it is assumed that $\psi_{c,\ell,j} = 1$; then the functional $\Psi(t)$, defined by equation (27), reduces to the number of available nodes participating in maintaining the quorum. For systems with differentiated roles or non-equivalent validators, the values of $\psi_{c,\ell,j}$ can be set in accordance with the adopted consensus policy.

We formulate the quorum condition as follows:

$$\Psi(t) \geq \Psi^{\min}, \tag{28}$$

where $\Psi^{\min}$ is the minimum acceptable value of the quorum assurance functional to maintain the operability of a blockchain-oriented distributed information system.

Equation (28) serves as a formal criterion for the admissibility of the current set of available nodes. Accordingly, a control action generated by Equation (23) can be considered admissible only if, after its execution, the value of the functional $\Psi(t+1)$ does not fall below the threshold value $\Psi^{\min}$.

Taking into account the constraints (18)–(21) and the quorum condition (28), the set of admissible control actions is defined as

$$A^{adm}(t) = \left\{ A_R(t) \,\middle|\, \begin{matrix} conditions\ are\ met\ (18)-(21) \\ \Psi(t+1) \geq \Psi^{min} \end{matrix} \{\} \right\}. \tag{29}$$

Then the resource and quorum control problem reduce to selecting a control decision that minimizes the resource deviation functional (22) over the set of admissible actions (29):

$$A^*(t) = \arg \min_{A_R(t) \in A^{adm}(t)} J_R(t). \tag{30}$$

Equation (30) integrates the resource and quorum components of the model. Unlike Problem (23), where the solution is selected based solely on the resource criterion, in Equation (30) the admissibility of an action is also determined by the condition that the quorum is maintained after the resource allocation changes.

To describe the system's transition between states, we introduce a generalized state:

$$\Omega(t) = \left\{ \bar{S}(t), \bar{Q}(t) \right\}. \tag{31}$$

In equation (31), the vector $\bar{S}(t)$ (3) reflects the aggregated resource state of the system; $\bar{Q}(t)$ (26) describes the availability state of nodes relevant to the quorum.

The system's transition to a new state under the action of the optimal control decision $A^*(t)$ is given by

$$\Omega(t+1) = \Phi\left(\Omega(t), A^*(t)\right). \tag{32}$$

where $\Phi(\cdot)$ is the system transition operator between discrete time steps.

Then the transition

$$\Omega(t) \to \Omega(t+1) \tag{33}$$

is considered admissible if the solution $A^*(t)$ belongs to the set $A^{adm}(t)$ (29).

Thus, relations (24)–(33) define the quorum component of the mathematical model and formalize the conditions for the admissibility of transitions of a blockchain-oriented distributed information system between states in a multi-cloud environment. Consequently, we present the mathematical model for managing computational resources and ensuring quorum in a blockchain-oriented distributed information system in a multi-cloud environment as a conditional minimization problem:

Сучасний стан наукових досліджень та технологій в промисловості. 2026. № 2 (36) *ISSN 2522-9818 (print)*
Innovative technologies and scientific solutions for industries. 2026. No. 2 (36) *ISSN 2524-2296 (online)*

$$A^*(t)=\arg\min_{A_R(t)} J_R(t),\begin{cases}\sum_{\ell=1}^{L}\sum_{j=1}^{N_{c,\ell}}\left(\bar{r}_{c,\ell,j}+\bar{u}_{c,\ell,j}\right)+\bar{S}_c\preceq\bar{R}_c;\\ \bar{r}_{c,\ell,j}^{\min}\preceq\bar{r}_{c,\ell,j}(t+1)\preceq\bar{r}_{c,\ell,j}^{\max};\\ \chi_{c,\ell,j}(t+1)=1;\\ v_{c,\ell,j}\in V^q;\\ \Psi(t+1)\geq\Psi^{\min};\\ \Omega(t+1)=\Phi\left(\Omega(t),A^*(t)\right).\end{cases} \quad (34)$$

In Equation (34), the objective function $J_R(t)$ defines the criterion for minimizing the total unregulated resource deviation, while the set of constraints specifies the resource feasibility of control actions, the limits of permissible resource allocation, the conditions for stable node operation, quorum assurance, and the admissibility of system transitions between states.

5.4. Simulation study of the model and analysis of the results

A simulation study was conducted to verify the performance of the developed mathematical model for managing computing resources and ensuring quorum in a blockchain-oriented distributed information system within a multi-cloud environment. The study examined a discrete interval of 120 cycles, divided into three phases: nominal operation mode, resource shortage, and degradation of node availability. This division allowed for a sequential assessment of the model's behavior under conditions of normal operation, local growth in resource demand, and deterioration of node availability relevant to quorum maintenance.

Figure 2 shows the trends of key normalized indicators of the simulation model: the aggregated system state vector $\bar{S}(t)$, the quorum assurance functional $\Psi(t)$, and the resource deviation functional $J_R(t)$. Normalization was applied to bring the indicators to a common scale and enable their comparative visual analysis within a single graph.

Figure 2 shows that in the initial simulation phase, the values of $\bar{S}(t)$ remain at a relatively low level, while $\Psi(t)$ is near the upper limit, corresponding to a stable quorum. In the resource shortage phase, an increase in $\bar{S}(t)$ is observed, along with the appearance of peaks in the $J_R(t)$ function, reflecting an increase in unregulated resource deviation as the load increases. In the final phase, corresponding to a degradation in availability, the level $\Psi(t)$ decreases, while the values of $\bar{S}(t)$ remain within the range characteristic of system operation following resource adaptation. This indicates that at this stage, maintaining a quorum of available nodes becomes the determining factor for the acceptability of decisions.

The summarized results of the simulation study by phase are presented in Table 1.

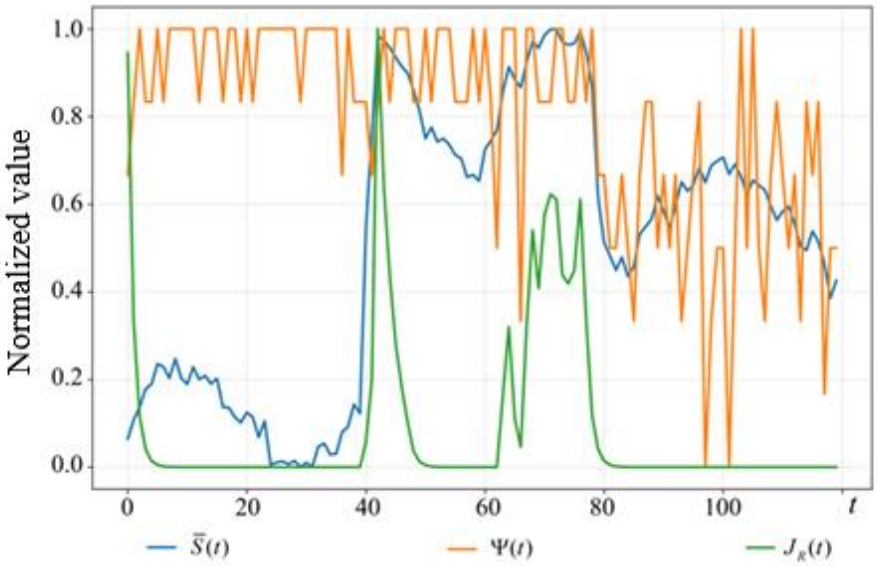

Fig. 2. Trends in key normalized indicators of the simulation model

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ISSN 2524-2296 (online) Innovative technologies and scientific solutions for industries. 2026. No. 2 (36)

Table 1. *Generalized results of the simulation study of the model by scenario phases*

Simulation phase	Number of cycles	$\bar{S}(t)$, average	$\bar{Q}(t)$, average	$\Psi(t)$, average	$J_R(t)$, average	Average total resource deficit	Proportion of allowed transitions
Nominal mode	40	0.531	0.958	8.625	0.0013	0.000	1.000
Resource deficit	39	0.823	0.926	8,333	0.0086	2.453	0.974
Degradation of availability	41	0.714	0.710	6.390	0.0001	0.000	0.805

An analysis of the data in Table 1 shows that, in nominal mode, the model operates under the most favorable conditions: the average value of $\bar{S}(t)$ is 0.531, the average value of $\Psi(t)$ is 8.625 with a minimum permissible quorum level of 6, and the proportion of valid transitions is 1.000. This confirms that, in the absence of resource shortages and with high node availability, the model generates control actions that do not violate either resource or quorum constraints.

During the resource shortage phase, the average value of the aggregate state $\bar{S}(t)$ increases to 0.823, and the average total resource shortage is 2.453. At the same time, the average value of the functional $J_R(t)$ increases to 0.0086. This means that under increased load, the model correctly detects an increase in resource deviation and shifts the decision-making process into active resource reallocation mode. At the same time, the average value of $\Psi(t)$ remains at 8.333, and the proportion of valid transitions is 0.974, indicating that a majority quorum is maintained in most cycles even in the presence of a local resource shortage.

The availability degradation phase is characterized by a different dominant factor. In the absence of an average resource shortage, the value of $J_R(t)$ practically approaches zero, while the average proportion of available nodes $\bar{Q}(t)$ decreases to 0.710, and the average value of $\Psi(t)$ decreases to 6.390 – that is, it approaches the quorum threshold. As a result, the proportion of valid transitions decreases to 0.805. The obtained result confirms that in this phase, it is precisely the quorum constraints defined by relations (28)–(30) that determine the validity of control actions much more strongly than the resource component of the model.

Overall, the results of the simulation study confirm the validity of the developed model and the correctness of the combination of its resource and quorum components. Equations (13)–(23) describe the redistribution of resources and minimize the resource deviation functional $J_R(t)$, while equations (24)–(33) constrain the set of feasible solutions with conditions for quorum preservation and the admissibility of transitions between states. The obtained values of the indicators show that the model adequately responds to changes in the system's operating mode: in the resource shortage phase, it is sensitive to the deterioration of the resource state, and in the availability degradation phase, to the reduction in the number of nodes sufficient to maintain a quorum.

Thus, the simulation study confirmed that the developed mathematical model is suitable for describing the processes of managing computing resources and ensuring quorum in a blockchain-oriented distributed information system in a multi-cloud environment.

6. Discussion of the research results

The results obtained should be viewed as an advancement in approaches to describing multi-cloud applications, with a primary focus on architectural deployment models and requirements for multi-cloud interaction. Study [27] demonstrates that for multi-cloud applications, the key issues are component portability, the concurrent execution of services across multiple cloud environments, and the alignment of architectural solutions with infrastructure properties. The proposed model specifies these provisions at the level of mathematical description by separating the set of cloud environments, the set of architectural levels, the set of nodes, and the vectors of available and allocated resources. This approach allows for a transition from a general architectural representation of a multi-cloud system to a formalized scheme for managing its resource state.

Compared to approaches focused on cross-data-center virtual machine scheduling, the results obtained here have a broader scope of generalization. In particular, in [27], blockchain is used as a distributed ledger for exchanging status information between data centers during the scheduling and migration of virtual machines, which allowed for a reduction in the number of service messages and a reduction in communication latency. In the developed model, the blockchain-oriented nature of

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the system is accounted for in a different context: control is linked to the generalized redistribution of heterogeneous resources among nodes at different architectural levels in a multi-cloud environment. This allows for the description of system states and control actions within a single formalized representation.

A concept that is conceptually similar is the approach to multi-cluster resource quota management in Kubernetes environments. The study [28] proposes a combination of predictive and reactive quota scaling based on Karmada, where decisions are made based on load monitoring and forecasting data. This approach is valuable from the perspective of practical implementation of dynamic resource reallocation; however, it is focused on quotas in a multi-cluster environment and does not account for the requirements for maintaining a quorum of nodes in a blockchain-oriented system. In the proposed model, the aggregated state vector $\bar{S}(t)$, defined by equation (3), is used as the basis for generating control actions according to equations (13)–(23), and the admissibility of such actions is subsequently verified with respect to quorum constraints. This constitutes the fundamental difference between the proposed approach and purely quota-based scaling.

An important area of related research is consensus-oriented orchestration of distributed services. In [29], it is shown that for distributed microservice environments, a decentralized approach to orchestration is appropriate, one that utilizes a consensus mechanism, dynamic leader election, and distributed logging. In this work, the main focus is on a mathematical model that combines the resource state of nodes, their availability, and the conditions for the system's transition between states. That is why the quorum is described through the set of nodes V^q, the availability state vector $\bar{Q}(t)$, the quorum satisfaction functional $\Psi(t)$, and the set of admissible control actions $A^{\text{adm}}(t)$. This framework creates a formal basis for the subsequent synthesis of control algorithms that are consistent with quorum requirements.

It should be noted that in current research on blockchain consensus, the primary focus is often on security, survivability, and resistance to attacks, as well as trade-offs between different classes of protocols. Source [30] systematizes issues of security and reliability of consensus mechanisms and demonstrates that the choice of protocol significantly influences the properties of a distributed system. The proposed model operates at a different level of abstraction and determines under which resource conditions and with which composition of available nodes a control decision is permitted that does not violate quorum maintenance requirements. Thus, its advantage lies in combining the resource and quorum components within a single mathematical framework.

The results of the simulation study confirm the feasibility of this combination. As shown in Fig. 2, in nominal mode, the values of $\bar{S}(t)$ remain in the lower range, while $\Psi(t)$ remains near the upper limit, which corresponds to a stable quorum. During the resource shortage phase, an increase in $\bar{S}(t)$ and the appearance of peaks in $J_R(t)$ are observed, reflecting an increase in unregulated resource deviation as the load increases. During the availability degradation phase, the preservation of the quorum of available nodes becomes the determining factor for the admissibility of decisions, manifested in a decrease in $\Psi(t)$ to a level close to the threshold value of $\Psi^{\min}$.

The data in Table 1 quantitatively confirm this pattern. In the nominal mode, the proportion of admissible transitions is 1.000, the average value of $\Psi(t)$ is 8.625, and the average total resource deficit is zero. In the resource deficit phase, the average value of $\bar{S}(t)$ increases to 0.823, the average total resource deficit is 2.453, and the average value of $J_R(t)$ reaches 0.0086. At the same time, the average value of $\Psi(t)$ remains at 8.333, indicating that the quorum is maintained in most cycles. In the availability degradation phase, there is no average resource deficit; the value of $J_R(t)$ practically approaches zero, but the average value of $\bar{Q}(t)$ decreases to 0.710, and $\Psi(t)$ to 6.390, as a result of which the proportion of admissible transitions decreases to 0.805. This confirms that the model correctly distinguishes between situations dominated by resource constraints and situations in which quorum conditions become decisive.

The results obtained suggest that the proposed model adequately describes the process of managerial decision-making in a multi-cloud environment under various system operating modes. Its strength lies in the fact that the resource component, represented by equations (13)–(23), and the quorum component, represented by equations (24)–(33), operate in concert within a single mathematical framework. This is precisely what makes it possible to reject a resource-efficient

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action if, after its execution, the quorum condition is violated.

A limitation of the current version is the abstract definition of the threshold value Ψ^{min} without reference to a specific consensus protocol. Further research should focus on parameterizing the model for protocols in the PBFT, Raft, or Tendermint families, as well as on a quantitative comparison of the quality of control decisions in scenarios with varying load intensities and different degrees of degradation in the set of available nodes.

7. Conclusions

As a result of this study, a mathematical model has been developed for the first time to manage computing resources and ensure quorum in a blockchain-oriented distributed information system in a multi-cloud environment. Compared to existing models, this model takes into account a set of cloud platforms from different vendors, the system's multi-level architecture, the aggregated resource state of nodes, their availability, and formalized quorum conditions, which made it possible to present the process of making management decisions regarding resource reallocation and maintaining system operability within a single mathematical framework.

Based on the research results, the multi-cloud deployment of components of a blockchain-oriented distributed information system was formalized based on the separate representation of a set of cloud environments, a set of architectural levels, a set of nodes, and vectors of available and allocated resources. This allowed for a correct description of the system as a control object in a multi-cloud environment and the specification of resource balance constraints for each cloud platform.

A mathematical description of the process of managing computing resources was developed based on the aggregated system state vector, node resource demand vectors, control actions, and conditions for permissible resource reallocation. This made it possible to formalize changes in the resource state of nodes under conditions of resource heterogeneity, dynamic load changes, permissible resource allocation limits, and stable node operation.

Formalized conditions for ensuring a quorum of available nodes and the admissibility of system transitions between states were determined, for which a subset of nodes relevant for maintaining the quorum, a state vector of their availability, a quorum assurance function, and a set of admissible control actions were introduced. This allowed for the integration of the resource and quorum components within a single mathematical control model.

The results of the simulation study confirmed the effectiveness of the proposed model under conditions of nominal operation, resource shortage, and degradation of node availability. It was established that in the event of an increase in load, the model correctly captures an increase in resource deviation, and in the event of a decrease in node availability, the condition for ensuring quorum becomes the determining constraint on the admissibility of control decisions.

The results obtained can be used for the further development of methods for optimizing resource management and ensuring quorum in blockchain-oriented distributed information systems in a multi-cloud environment.

Conflict of interest

The author declares that he has no conflicts of interest regarding this study, including financial, personal, or authorship-related conflicts, or any other conflicts that could influence the study and its results as presented in this article.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

The author confirms that he did not use artificial intelligence technology in the creation of this work.

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МОДЕЛЬ УПРАВЛІННЯ РЕСУРСАМИ ТА КВОРУМОМ БЛОКЧЕЙН-ОРІЄНТОВАНОЇ РОЗПОДІЛЕНОЇ ІНФОРМАЦІЙНОЇ СИСТЕМИ В МУЛЬТИХМАРНОМУ СЕРЕДОВИЩІ

Предметом дослідження є математична модель управління обчислювальними ресурсами й забезпечення кворуму блокчейн-орієнтованої розподіленої інформаційної системи в мультихмарному середовищі. **Метою** є розроблення теоретико-множинної моделі, що формалізує мультихмарне розміщення компонентів блокчейн-орієнтованої розподіленої інформаційної системи, зважає на її багаторівневу архітектуру, гетерогенність доступних ресурсів, агрегований ресурсний стан вузлів, їх доступність і умови забезпечення кворуму під час функціювання за змінного навантаження. **Методи**. Щоб досягти окреслену мету, впроваджено системний аналіз для формалізації структури системи й взаємозв'язків між її компонентами; математичне моделювання – для побудови формального опису мультихмарного середовища, ресурсного стану вузлів, керівних дій і кворумних обмежень; статистичний аналіз – для оброблення, агрегації та нормалізації телеметричних показників; теорія прийняття рішень – для формування умов допустимого перерозподілу ресурсів; імітаційне моделювання – для перевірки працездатності розробленої моделі за умов змінного навантаження, ресурсного дефіциту й варіативної доступності вузлів. **Результати**. Уперше розроблено формалізовану теоретико-множинну модель управління обчислювальними ресурсами й забезпечення кворуму блокчейн-орієнтованої розподіленої інформаційної системи в мультихмарному середовищі, яка, на відміну від наявних підходів, поєднує в межах єдиної уніфікованого середовища подання мультихмарного середовища як сукупності хмарних платформ різних вендорів, багаторівневої архітектури системи, агрегованого ресурсного стану вузлів, умов допустимого перерозподілу ресурсів і заданих вимог до забезпечення кворуму. Запропоновано множини хмарних середовищ, архітектурних рівнів і вузлів системи, упроваджено вектори доступних і виділених ресурсів, агрегований вектор стану системи, функціонал ресурсного відхилення, функціонал кворумної забезпеченості та множину допустимих керівних дій. Імітаційне дослідження підтвердило працездатність моделі в умовах номінального функціювання, ресурсного дефіциту й деградації доступності вузлів. Це дало змогу подати процес прийняття рішень щодо перерозподілу ресурсів і підтримки працездатності системи в межах єдиного математичного подання. **Висновки**. Запропонована модель сприяє формалізованому опису процесів управління обчислювальними ресурсами й забезпеченню кворуму блокчейн-орієнтованої розподіленої інформаційної системи в мультихмарному середовищі та може бути використана як основа для подальшого розроблення методів оптимізації керівних рішень і експериментального дослідження ефективності функціювання системи за умов динамічної зміни навантаження й часткової деградації вузлів.

Ключові слова: математична модель; управління ресурсами; кворум; блокчейн; інформаційна система; хмара.

Бібліографічні описи / Bibliographic descriptions

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