Process management of heterogeneous services in a digital university based on modified GERT networks

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Abstract. The research is devoted to the issues of managing the processes of the information and computing environment in a digital university, which have a distributed, heterogeneous, probabilistic, poorly controlled nature. To improve the efficiency of managing the processes in a digital university, the authors of the research analyzed scientific papers in the field of the information technology infrastructure of organizational and economic systems and universities, formulated the basic principles of information technology infrastructure in a digital university within the conceptual framework of innovative infrastructure for modern organizations, developed a generalized scheme of IT services in a digital university, and elaborated a mathematical apparatus of modified GERT networks to control the processes of heterogeneous services in a digital university. The practical value of the research results is related to the development of new approaches to information management and processes of a modern organization based on the principles of consistency, complexity, and compliance with an appropriate balance between the distribution and integration of data flows. These developments can be replicated with certain modifications to a wide range of organizational and economic systems that are in the stage of digital transformation.

1 Introduction

The direction of modern development for universities is associated with the formation of an environment for the effective construction of skills, competencies, and scientific and practical knowledge given the personal characteristics and needs of students and dynamically changing requirements from the state and business to professional expertise and the level of digital competence. A digital university, like any organizational and economic system, should flexibly and promptly respond to changes taking place in the society and the economy, both in the context of training highly qualified specialists and in the context of the formation of new scientific knowledge and innovations [1].

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Infrastructure solutions in a digital university should ensure an integrated information and communication environment for the organization and implementation of educational, project, research, and innovation activities and solutions to applied problems. Following the *Strategy of Digital Transformation for the Branch of Science and Higher Education*, a digital university project is associated with the development of digital services that should support all processes implemented at the university and all interested participants: students, research and teaching staff, administrative and managerial personnel, applicants, graduates, and employers. The fundamental problems and tasks are as follows: (1) development of the university digital environment; (2) introduction of end-to-end technologies; and (3) elaboration of information technology infrastructure for the development and effective implementation of a range of heterogeneous IT services focused on supporting the processes performed in the areas of the university activities and ensuring interaction with partners, employers, and applicants [2].

The information and technical infrastructure of modern organizational and economic systems is a complex of software and computing systems, data storage and transmission systems, and sets of essential information services; it forms the basis for the functioning of IT services. Practical solutions of the IT infrastructure of the organization in the context of digital transformation provide for the consolidation of computing systems and data storage resources containing means of virtualization and organization of cloud infrastructure platforms.

The fundamental problems in the field of digital transformation in the university as an organizational and economic system are as follows: (1) lack of a unified digital environment; (2) inefficient introduction of end-to-end technologies; and (3) insufficient development of information and technical infrastructure for the development and effective implementation for a range of heterogeneous IT services focused on supporting the processes performed in the areas of the university and ensuring interaction with partners, employers, and applicants.

Implementing the transition to a digital university imposes requirements for (1) the organization of the implementation of core business processes and (2) the development of corporate culture, digital competencies of employees, and infrastructure solutions and technologies. Therefore, innovative infrastructure solutions in a digital university should be formed given the interconnection and interaction of the main components in the scientific and educational environment that cover educational, design, research, administrative, and economic activities and provide their support with IT services.

One of the main approaches to solving problematic issues of effective management in digital university processes can be modeling operations of computational data processing of heterogeneous environments of digital services in the organizational and economic system of the university based on modified Graphical Evaluation and Review Technique (GERT) networks. Thus, the proposed approach makes it possible to manage the information and technical infrastructure in a digital university on the principles of heterogeneous process systems; it is better for the digital environment and, ultimately, the university quality management system.

2 Materials and methods

The research aimed to develop a mathematical apparatus of modified GERT networks for managing information and computing processes in a multiservice environment of a digital university.

The object is the IT services of a digital university.

The subject is the processes of heterogeneous service-oriented systems.

In order to achieve this goal, the following tasks were formulated and solved:

- To analyze and summarize the research results in the field of the information technology infrastructure of organizational and economic systems and universities in the context of digital transformation;
- To formulate general principles for the organization and functioning of the information technology infrastructure of the digital university;
- To develop a generalized scheme of IT services in a heterogeneous distributed digital environment of the university;
- To develop a mathematical apparatus of modified GERT networks for managing information and computing processes of a multiservice environment of a digital university.

The initial materials for the research were as follows: (1) data from scientific research in the field of the information technology infrastructure of organizational and economic systems and universities, and (2) methodologies for modeling-controlled processes of heterogeneous systems. The authors used information from the official website of the international partner business network of universities, official websites of leading Russian universities, and open Internet sources.

The following scientific methods were used to conduct scientific research: (1) method of system analysis – to study the features and problematic aspects of IT services and information technology infrastructure of a digital university; (2) method of logical analysis and synthesis – to generalize the results of scientific research to form the basic principles for the organization and functioning of the information technology infrastructure in a digital university; (3) method of scientific description and system integration – for the visual presentation of scientific research results to develop a generalized scheme of the service information and technical infrastructure of a digital university; (4) method of formalization – to model the processes of servicing the digital environment of the university; and (5) mathematical method of modified GERT networks – to manage information and computing processes of heterogeneous services of a digital university. The use of these methods helped formulate a scientific hypothesis of using the formalized apparatus of GERT networks to improve the efficiency of information and computing processes management in a distributed, heterogeneous, service-oriented environment of a digital university.

The research in the field of the information technology infrastructure of organizational and economic systems, to which the structure of a modern digital university can be attributed, has been conducted for many years and often has a non-systemic or contradictory nature due to the different points of views based on the concept of geographically distributed high-performance resources in the environment of information management systems.

The research directions in this area are represented by theoretical developments of the basics and practical solutions to the problems of combining geographically distributed high-performance resources in the environment of information management systems [3; 4]. Generalization of available solutions and development of an approach to the selection of IT services to ensure optimal support of processes implemented in distributed systems are presented in the scientific work of A. S. Rykov [5]. Generalization of studies on theoretical and practical aspects of the development of distributed systems, resource management systems, and distributed data processing and the elaboration of an architectural solution for an industry digital research platform is presented by V. A. Kondrashev [6]. Models and algorithms for managing web services of an educational institution, mechanisms, and tools for organizing, integrating, and managing heterogeneous web services have also been considered by some researchers. The research of algorithms and models for processing requests of interactive services for info-communication networks was conducted by D. I. Parfenov [7], while the management of heterogeneous information resources was investigated by S. E. Greger [8; 9; 10].

Over the past decades, methods, models, and mathematical and software solutions for managing IT services of geographically distributed systems have been widely researched and developed given their flexibility and functionality. In addition, many studies were conducted to solve integration problems for providing heterogeneous services in educational institutions to support their activities. The tasks considered solving the problems of departments integrating information systems to create a single integrated system, increasing the availability of information support for users, and improving the manageability of services.

The research on the development of methods and iterative algorithms for multi-level group management of resources and data of systems that ensure the optimal connection of clients and servers for organizing network interaction and rapid exchange of information was conducted by A. G. Tormasov. The author presented an approach to creating distributed virtualized environments designed to host, store, and manage resources and data using mathematical models to describe such environments. The research of methods and algorithms for managing the distribution of resources and the organization of distributed systems was carried out. The research was based on discrete mathematics and algebra, computational mathematics, systems theory, and system programming. The critical concept considered by the author was *mobility*. In accordance with this concept, (1) the developed solution should ensure that the service is provided to the user regardless of the devices they use, (2) computing resources and data should follow the user, (3) data should move between physical media, regardless of network access and the state of the external environment. A. G. Tormasov also used algorithms for assembling and disassembling data and organizing calculations based on operations on Galois fields and developed a system of mathematical and simulation models, algorithms, and methods for managing resources of a virtualized distributed environment. One of the principles was the principle that the service provided could be obtained from any server of the system [5].

Mathematics and software for transaction management processes in distributed heterogeneous real-time information systems (IS) to improve the quality and efficiency of data generation in complex structured parametric queries were developed by S. A. Rykov. As a result of the analysis of the problem for transaction management problems in heterogeneous distributed ISs and control of their states using mathematical transaction management tools, the solution for the problem of breaking the deadlock for transactions working with locks in the operational conditions of parallel exchange is given. The basis for detecting a deadlock situation is the execution of operations on the transaction waiting for graph – an oriented bipartite graph $G = (W, E)$, with vertices corresponding to transactions and lock objects. An angle from the vertex-object to the vertex-transaction exists only if the transaction is waiting for the lock request of this object to be satisfied. The mathematical description of the transaction coordinator in case of synchronous deadlock is performed using the reduction of the expectation graph, which provides the necessary speed in conditions of deadlock situations in transaction management [5].

The development of solutions for resource allocation and task planning in problem-oriented distributed computing environments of systems is considered in the research by A. V. Shamakina. The presented problem-oriented resource planning algorithm was also developed based on the task graph – a marked weighted oriented acyclic graph. Based on it, a resource planning algorithm has been developed in the form of a three-level structure of procedures [11].

Concerning the information and technical infrastructure of the university, P. A. Ordyntsev modeled the information space of the university with the use of mathematical apparatus. The model is described in terms of mathematical divisions, instances of the information system for divisions, and information entities or their attributes in the system. The ownership rights of the information entity were determined; on their basis, the system could use or modify this entity. A global data model was formed and indicated their

belonging to specific information systems and the state of ownership rights in the form of a discrete three-dimensional matrix. The author proposed a methodology for integrating services into a single information system of the university based on solving the problem of synchronizing familiar entities and building links between the components of this system. The models were implemented on the basis of a routing algorithm using a subscription mechanism [12]. Instrumental support for the proposed algorithms and methods was provided by the service bus. The author developed an integration platform combining services into a single information system with a developed routing algorithm and connecting services implemented on various platforms.

The approach of P. A. Ordyntsev can be considered during the transition period for the formation of a single platform for IT solutions for a digital university and the need to combine legacy systems.

The research in the field of heterogeneous environments of controlled process systems is of particular interest. In this direction, solutions based on software complexes of service-oriented architecture models (COA or SOA) were actively developed to transform a heterogeneous system environment into a homogeneous one. The authors of the research on heterogeneous environments have found that the SOA model (1) helps use loosely coupled distributed replaceable components with standardized interfaces of interaction following protocols, (2) can be implemented using technologies of the various spectrum, and (3) provides the opportunity to use independent services called by standard methods. A block diagram of an algorithm for selecting an information flow from a homogeneous space was proposed by the researcher E. A. Lomov, and an algorithm and software for transforming heterogeneous information space into a homogeneous information environment were developed. The elaborated software tools for media stream management processes in the conditions of heterogeneity of the real-time system helped increase the efficiency of interaction [13].

In the context of effective process management in heterogeneous environments in a digital university, A. I. Tikhomirov conducted research related to the analysis of requirements for the efficiency of performing various tasks, primarily tasks with high priority, for the quality of organizing access to network resources and the quality of university resource management. In connection with the work carried out by A. I. Tikhomirov, (1) algorithms and architecture of the task management system of a heterogeneous geographically allocated network of supercomputing centers for collective use and (2) a document-oriented model of data storage and presentation of a unified information subsystem of the task management system based on a distributed Database Management System (DBMS) were proposed [3]. The developed architecture of the control system organizes a decentralized scheme of interaction of equal dispatchers in a geographically allocated network of supercomputing centers. Methods and algorithms for scheduling computing tasks in a distributed network, performed by priorities and specified time conditions (minimizing the average task execution time), were developed using the inverse form of the planning auction in distributed systems. The method assumes the ranking of incoming tasks in the global queue by their priorities and the distribution of tasks as a result of an auction, the participants of which are dispatchers of free computing resources necessary to complete the task and whose rates depend on their workload [4].

The problem of efficient and flexible planning of incoming data processing tasks on the available computing resources of distributed data processing systems was considered by I. A. Golubev. Based on the classification of data processing tasks due to their resource requirements, a mathematical model of task planning was developed based on solving the assignment problem, the algorithm of the nearest neighbor method modified by the localized hashing method, calculating the hash value for categorical and numeric data types separately [14].

Some authors conducted scientific research in the field of effective content management based on SMS procedures. For example, A. V. Ivanov proposed an architectural solution and software infrastructure of a portal SMS system and a software solution for content management in the integration platform of an Internet portal based on SOA principles tested in educational and scientific organizations. The functioning of the system is described by mathematical models given various modes of operation. Changes in the system parameters were studied based on statistical analysis using a threshold autoregression (TAR), considering the difference in the dynamic nature of the time series. Modeling the average query execution time under different conditions describes the dynamics of the source efficiency indicator by a dynamic stochastic observation system. The developed model helps determine the necessary realization of the Internet portal by the specified modes of operation [15].

In this research, elements of the above-mentioned scientific approaches and methodologies were used and successfully applied to improve the efficiency of managing the processes in a digital university based on modeling computational data processing operations of heterogeneous digital service environments.

Dynamical modeling methods of computational processes in heterogeneous media are based on the hypothesis of adequacy, suggesting that if the process is managed in terms of a multi-case scenario, one could expect a known probability of the match of the model of the simulated system concerning the purpose of modeling [10, 16].

3 Results

The innovative infrastructure in a digital university is a complex, multicomponent, multilevel infrastructure; on its basis, heterogeneous IT services are implemented and developed. In addition, various models, algorithms, and tools are developed and managed.

Process management of heterogeneous services in a digital university is carried out based on the main principles in the information and technical infrastructure in a digital university, which is considered an interaction system of individual subsystems and services in digital platforms [4; 5; 15].

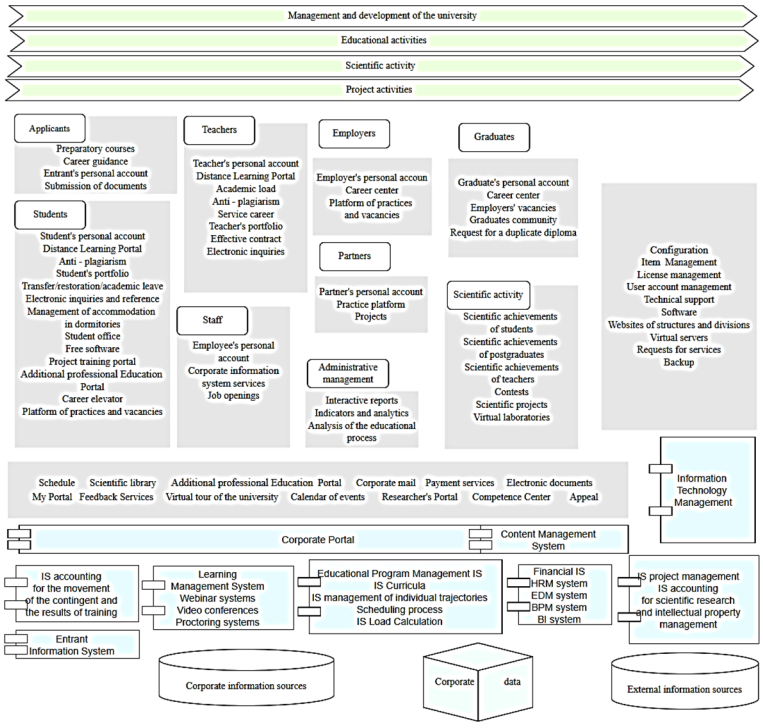
The analysis of the research in the field of information technology infrastructure for organizational and economic systems and universities helps the authors formulate basic principles for building a model in a digital university infrastructure:

- The information and computing environment of the university should be implemented based on a platform solution represented by a set of heterogeneous services and data located in various nodes of the network space and include systems necessary for the organization and effective management of all components based on big data analysis and integrated resource management received from any server of the system.
- The architectural informative systems and services of the university should be adaptive and flexible for effective business decision-making in modern dynamically developing and changing conditions, and in the context of this principle, the IT service in a digital university is considered a digital service provider, a kind of *product*, and, as a rule, in an intangible form [17].
- First of all, IT services in a digital university should support end-to-end processes and provide IT support for educational, project, research, and innovation activities, including in a network form.
- In addition to software services that implement the processes of searching and tuning to consumer requirements, the information technology infrastructure of a digital university in the service-oriented architecture concept should also include

infrastructure services of hardware, software, and information platforms that support dynamic links with other services [15].

- The primary goal of developing methods for managing heterogeneous services in supercomputer centers for the collective use of the digital environment in the university should be to ensure the necessary functionality of services, accessibility, operability, and efficiency.
- An urgent task of a digital university is the effective management of distributed information resources and web content and the provision of service access to them for various users. This forms the requirements for the applied algorithms and software infrastructure for the organization of distributed data processing and management of unstructured content throughout the entire lifecycle.
- IT solutions within the digital university infrastructure should ensure the effective functioning of content management systems as an integral component of the corporate system and provide training and teamwork with information of various forms. At the same time, the content management system with an open architecture, included in the Internet portal and supporting work with content integration tools from different sources, provides interaction with external information sources, search, data access, and publication, including based on service-oriented models.

Based on the above principles of the general model in digital university infrastructure and the generalization of approaches and practical solutions to the formation of digital university services [18; 19; 20; 21], the authors developed a generalized scheme of IT services in a digital university (Figure 1).



Note: * IS – Information System, HRM – Human Resource Management, EDM – Electronic Document Management, BPM – Business Process Management, BI – Business Intelligence.

Fig. 1. Generalized scheme of digital University information technology services. *Source*: Compiled by the authors.

Fig. 1 shows the main IT services that provide support in the implementation of university processes, the growth of scientific potential and digital competencies, and the organization of effective collaborations and partnerships.

Thus, the infrastructure in a digital university with distributed process management can be represented as a complex, multicomponent, multilevel heterogeneous environment, including, among other things, a set of IT services as tools for access, distribution, integration, and management of data and processes related to scientific, educational, organizational, managerial, and administrative activities of the organization. The integration of systems and heterogeneous data and processes of the university infrastructure, coming from various internal and external information sources and systems, ensures the provision of different IT services to interested parties (students, professors, partners, employers, etc.) in all areas of activities in the university. The quality of the IT services provided is influenced by the efficiency and operability of the processes of transmission, processing, and integration of heterogeneous data and metadata in the information environment of the university, which is provided by algorithms and methods implemented in software tools aimed at organizing the interaction of programs, software complexes, and information systems of a digital university based on web-portal and cross-platform technology [15, 22; 23; 24; 25].

Currently, there are various approaches and a wide range of methods, models, and algorithms, as well as their various combinations, used for the effective organization of an integrated information and software communication environment and computing resources that form the IT infrastructure and participate in the implementation of IT services, ensuring their availability, effective functioning, and management.

One of the effective tools for the management of digital innovation infrastructure in the university is distributed integrated information technology and heterogeneous network services [26; 27].

The authors of this research proposed a mathematical apparatus of modified GERT networks as an effective modeling tool for the computational processing of data across heterogeneous environments of digital services [28; 29].

GERT networks help analyze the time characteristics of the network nodes for a distributed heterogeneous system and redistribute the computational load of heterogeneous networks without using additional labor-intensive load reduction methods in the system [16, 27; 30].

The mathematical apparatus of modified GERT networks is founded on the use of (1) an arbitrary number of extra real and stochastic limits of the GERT network node and (2) haphazard functions considered at the time of the network node activation as conditional probabilities of the outgoing arc for the network node [28; 29].

The authors of this research include the following main assumptions for modeling data processing operations in heterogeneous digital service environments based on GERT networks:

- A directed graph G of a GERT network consists of a nonempty set E of directed edges (*arcs*) and a nonempty set V of vertices (nodes). Let each edge be uniquely defined by its initial and final nodes (*edge* (i, j) is defined by the initial node i and the final j).
- Each node of the GERT network is activated with some probability. For a stochastic GERT network, the weight of the *arc* (i, j) is the vector $[p_{ij}, F_{ij}]$, where p_{ij} is the conditional probability of *arc execution* (i, j), provided that the node i is activated (probability of arc execution *(work)* (i, j)), and F_{ij} is the conditional distribution function of *arc* execution *time* (i, j), provided *that* (i, j) is executed.
- Each node of the GERT network has input and output activation functions that also affect the parameters of the activated node.
- The following can be used as network input functions of heterogeneous processes:

  - AND-function (the node is activated if the actions of all arcs incoming to the node are executed);
  - IOR-function (the node is activated if the actions of any arc included in the node are executed);
  - EOR-function (the node is activated if the actions of any arc or component are performed, provided that at a given time, the action of only one arc can be executed within that node).
- The following network output functions can be used:
  - Deterministic function (all arcs coming out of the node are executed if the node is activated);
  - Stochastic function (exactly one arc coming out of the node is executed with a given probability if the node is activated).

Evidently, by combining all input and output functions in a network of heterogeneous processes within the framework of the above assumptions, it is possible to implement six different types of nodes. Activation of any node of the network means that the system has entered a specific state and determines many possible further actions. One or more activities begin their execution immediately after the activation of the node that is their beginning. Node activation occurs if its input function is executed. After performing the output function of the activated node (starting the execution of the corresponding arc), it becomes inactive.

Thus, it can be assumed that a GERT network is a network with sources R and sinks S of the *working on an arc* type, in which each node belongs to one of six node types, the weight of the type $[p_{ij}, F_{ij}]$ with the above value is determined for each *arc* (i,j), and the initial distribution of network sources is set.

To model the processes of the data processing system of heterogeneous services, the authors introduce the following notation:

$$P(i) = \{j \in v | (i,j) \in E\},$$
$$S(i) = \{j \in v | (i,j) \in E\}, \quad (1)$$

$R(i)$ ={set of nodes reachable from node i (including i)},
$\bar{R}(i)$ ={{the set of nodes from which node i is reachable (including i)}.

Denote $G(i)$, where $i \in R$ is a subnet of the network G, built on the set of vertices $R(i)$.

Denote the set of network activation sequences by Ψ.

In this case, the set of activation sequences Ψ is valid if for any $W_1, W_2 \in \Psi,\ W_1 \neq W_2$, the paths W_1 and W_2 do not intersect, except if they use the same deterministic starting node and can use the same ending node [28].

Let D_{ij}^n be the execution time for the nth time of the arc (i,j).

To quantify the fault tolerance of a heterogeneous network for digital services, the authors of this research introduce the concept of a modified network (MG network), which, in essence, is a GERT network $G(V,E)$, satisfying the following conditions:

- The MG network has a single source and at least one drain.
- The MG network satisfies some limitations.
- During each project implementation, no more than one source is stimulated for each drain from which this drain is achievable.
- For each node i of the MG network, the following condition is met: If the node i is activated, the parameters of all arcs coming out of it are computable [28].
- In order to calculate the parameters of nodes with AND and IOR inputs, it is necessary to calculate the parameters of all incoming arcs of the network and know the probability of node activation that *generated* the process of simultaneous execution of events. Let the node $i \in V$ of the MG network $G(V,E)$ have more than one ancestor $(|P(i)| > 1)$, then for any $j,k \in P(i)$, the authors introduce the function $Pr(i,j,k)$, which is a set of nodes that are the nearest common ancestors

of the node i [28] and paths ending *arcs* $(j,i),(k,i)$:

$$Pr(i,j,k) = \{l | l \in \bar{R}(j) \cap \bar{R}(k), S(l) \cap \bar{R}(j) \cap \bar{R}(k) = \emptyset\}. \quad (2)$$

Similarly, for the node $i \in V$ of the MG network $G(V,E)$, having more than one descendent ($|S(i)| > 1$), for any j, k ∈ S(i), the authors introduce the function $Sc(i,j,k)$, which is a set of nodes that are descendants [28] of the nearest common node i and paths, starting with the arcs $(i,j),(i,k)$:

$$Sc(i,j,k) = \{l \in V | l \in R(j) \cap R(k), P(l) \cap R(j) \cap R(k) = \emptyset\}. \quad (3)$$

- For each node k of arbitrary cyclic structures C, there is a path from k to a node outside of C, such that $p_{ij} > 0$ for each arc (i, j) of this path [28].
- For any node i of the MG network G, having an IOR or AND inputs, for any $j,k \in P(i)$, $Pr(i,j,k) = \{1\}$, with 1 being the only node and 1 having a deterministic output.
- For every node i of the MG network G, having a deterministic input, for any $j,k \in S(i)$, $Sc(i,j,k) = \{1\}$, with 1 being the only node and 1 having an AND or IOR inputs.
- The implementation of the network is valid if, during execution, each of the activated nodes of the network is activated no more than 1 time; the implementation of the network is valid if, during execution, each of the activated nodes of the network is activated with a probability greater than $P_{max} > 0$; if more than one arc enters the node i of the cyclic structure C and at least one arc does not belong to the cycle C [28], then the node i has an EOR input; if more than one arc of the node i of the cyclic structure C exits and at least one arc does not belong to cycle C, then the node i has a stochastic output; if the node i with IOR or AND inputs belongs to the cycle, then the node j with a deterministic output, which is the stochastic beginning of the node i, belongs to this cycle. This limit guarantees that for any network, the number of operations is finite; therefore, the network is computable using computer technology.
- Many parameters are set for each node of the network (at least the possibility of activation).
- For each arc, the transformation functions of the network node parameters are specified.
- The source of the MG network is activated at time 0.

Stochastic parameters for the nodes of the MG network mean a certain distribution function of real random variables.

Calculating the stability (fault tolerance) of digital services of the MG network will be a set of R_r implementations grouped by r_k sinks. For the drain in each implementation, the probability of the network node activation (the probability of the implementation occurrence), the distribution function of the execution time for this implementation, and all additional parameters will be calculated.

Let r be an element for the set of realizations R_r with a drain r_k, then the probability of the drain activation r_k is as follows:

$$P_{rk} = \sum_r p_r. \quad (4)$$

Probability of the drain operation r_k by the time t under the condition of the drain r_k drain is activated (the distribution function of the drain $timer_k$):

$$F_{rk}(t) = p_{rk}(t)/P_{rk} = \sum_r p_r * F_r(t) / P_{rk}. \quad (5)$$

Thus, quantitative estimates of the probabilities of activating the network nodes for processes of a heterogeneous system of digital services, proposed by the authors, make it possible to predict the state of system processes and manage distributed processes of heterogeneous IT services based on the redistribution of the computational load of the network during service data processing.

4 Discussion

The research examines approaches to formalizing information and computing processes of distributed heterogeneous multiservice environments of a digital university. Modern publications related to the directions of digital transformation of universities are mainly focused on fundamental issues in the transformation of models and formats of educational services, scientific activities, development of human resources, interaction with partners, and industry and international cooperation. At the same time, the research on applied issues of developing fundamentally new or adapting existing models, technologies, and mechanisms for managing the processes of a digital university is often non-systemic or debatable.

The research in the field of digital transformation of higher education should use approaches to building the information, system, and technological architecture of a digital university based on the business logic of internal and external processes of the organization, so as not to limit, in the opinion of the authors, the possibility of optimal restructuring of processes in changing the goals and objectives of university management. The authors of this research propose an approach to system integration of heterogeneous IT services in the distributed digital environment of the university, which makes it possible to combine local processes into flexible managed process structures focused on key indicators of the activity of the organization, which include indicators of several local processes. For example, within the authors' generalized scheme of IT services in a digital university, it is possible to integrate the processes of the system corporate service *Accounting for the Movement of the Contingent and Learning Outcomes* and the external service *Distance Learning Portal*, which helps form a system end-to-end process *Student Preference Management* and improve the efficiency of decision-making by the educational department and the marketing service of the digital university on student loyalty issues.

Another feature of the research is the development of a mathematical apparatus of modified GERT networks for managing information and computing processes of heterogeneous services in a digital university. The practice shows that high-performance heterogeneous computing technologies used in the process of solving managerial, research, and practical production tasks are characterized by high throughput and reliability. During the use of heterogeneous services of the digital system, there is a decrease in the fault tolerance of the system, which is due to the specifics of the functioning of a heterogeneous computing platform and the features of modeling and management tools for processing heterogeneous data [26; 27]. The most common formalizations of the service processes for digital management of an educational institution at the hardware-computing and information level include parallel computing models, fuzzy set models, category theory [30], and cognitive models of oriented graphs, each of which is more or less focused either on the computational-transactional or information-algorithmic level of the system processing. The authors of the research suppose that along with some advantages, formal representations of this type do not sufficiently consider such significant management factors as risks of computing incidents and threats to information security. The analysis of the obtained research results helps conclude that it is advisable to use the proposed formalization tool for effective management of multiservice processes in a distributed digital environment of a digital university, which is characterized by a multivariance of events, a structural diversity of processes, and significant risks of computing incidents and information threats.

5 Conclusion

As a research result, the general principles for the information and technical infrastructure in a digital university are formulated, and a generalized scheme of IT services in a digital university is developed.

The authors have developed a mathematical apparatus of modified GERT networks to effectively manage the processes of heterogeneous services in a digital university.

The practical value of the research results is associated with the goals and objectives of the *Strategy of Digital Transformation for the Branch of Science and Higher Education*, aimed, among other things, at the development of new methods of mathematical modeling and digital management.

The authors' developments can be replicated with certain modifications to a wide range of organizational and economic systems that are in the phase of digital transformation.

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