UNIVERSITY OF INSURANCE, FINANCE AND ENTREPRENEURSHIP - SOFIA

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ABSTRACT

Development and Research of Applied Digital Economy Basis: Blockchain and Optional Approach

for awarding the educational and scientific degree "Doctor" under the doctoral program "Finance, Insurance and Insurance" in the professional field 3. 8. Economics

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The dissertation on the topic ‘Development and research of applied digital economy basis: blockchain and optional approach’ compiles 190 pages, including lists of acronyms used, graphs and tables, introduction, six chapters, general conclusion, bibliography. The dissertation depicts 60 figures and 8 tables. The bibliography covers 183 sources including books, articles, periodicals and non-periodic statistical and other publications, reports and online sources.

The dissertation defense will take place on 21st of June 2022 from …… hours in Hall ……. of the Higher School of Insurance and Finance (VUZF) at a meeting of the Scientific Jury, appointed by order of the Rector of VUZF. The defense materials are available to interested parties in ……

Dissertation general description

Topic relevance. The digital economy sets the vector which initiates social and economic systems of micro, meso-, and macro-levels to develop in the long term, requiring the research and comprehensive analysis of digital transformation processes. Previously a priority for individual innovative companies, digital transformation has become a massive phenomenon today, and related projects are vital for the success of respective companies and countries. At t he same time, the conversion is closely related to the trend of servitization of social and economic systems and is largely implemented on its basis. Moreover, this relationship and the mechanism for its implementation remain insufficiently studied, which necessitates the development of tools for its identification, assessment, and management.

Theoretical studies demonstrate that servitization and digital transformation of social and economic systems are based on the digital platforms that integrate economic, social, and technological processes and form digital service ecosystems. In fact, a new institution is emerging, a new category of business structures in the service sector. i.e., the service integrators' role in progressive economic development is significantly increasing. However, their functioning, management methods, network service interaction with other economic entities and many other issues remain insufficiently studied, hindering the development of companies-service integrators.

The above circumstances determine the topic relevance of the thesis research, both in terms of the formation and development of the modern economic theory (in particular, its sections related to the processes of servitization, structural, institutional transformations, the construction of the digital economy, etc.) and for increasing the scientific and methodological base of practically oriented tools for the digital transformation of social and economic systems based on the formation and development of the service integration institution.

A systematic analysis of the blockchain technology and features of its application, consideration of internal logic (encryption, consensus) are also

relevant. Simultaneously, one of the main problems of blockchain technology is the data reliability that determines the need for effective encryption algorithms. Such algorithms must ensure sufficient cryptographic strength for information on the network and allow the digital signature implementation.

Thesis connection with scientific programs, plans, and topics. The thesis was carried out within research work "Methodology for managing enterprises of different organizational and legal forms and forms of ownership" state registration number 0107U001146 (author - executive); "Methodology of social and economic, information and scientific and technical development of regions, industries, enterprises, and their associations" state registration number 0116U006782 (author - executive); "Structural transformations of the economy: macro-, meso-, and microlevels" (section "Multiprocessor computing systems in global optimization problems"), state registration number 0115U005679 (author - executive).

The purpose and objectives of the research. The thesis research purpose is to develop theoretical foundations and methodological provisions and scientific and practical recommendations for managing the digital transformation of applied economic systems based on the blockchain technology development and an optional approach; to improve the structure and increase the performance of multiprocessor systems adapted to the problems of the studied class of the digital economy, as well as introducing numerical and analytical algorithms and methods on the basis that can increase speed, accuracy, and reliability of experimental data processing.

Based on the literature sources review and the results of the analysis of the current state of the problems of digital economy and multiprocessor computing systems, it is necessary to perform such interdependent scientific tasks:

– analyze the problems and tasks of innovative blockchain technology as one of the components of the digital economy;

– analyze the theoretical foundations of the basic principles of functioning of blockchain technology, conduct a review of blockchain technology, consider the possibilities and its feasibility in the digital economy;

– explore and describe the main mechanisms for the blockchain technology implementation, give examples of ready-made solutions for the blockchain technology implementation, consider software tools and development features and their functioning;

– propose a new method for creating a fully scalable, evidence-based, and energy-efficient blockchain via a new consensus protocol, sharding, and distributed randomness generation;

– investigate the sustainability and reliability of the newly developed consensus method of the blockchain system;

– analyze the features of real options in the digital economy;

– develop new option constructions of real options in the digital economy;

– develop a new approach for option pricing based on Monte Carlo methods;

– show that the developed parallel algorithms of the Monte Carlo method are stable for any input data, have the maximum parallel form, and, therefore, the minimum possible implementation time on parallel computing devices;

− analyze the structure and functionality of multiprocessor computing systems for solving digital economy problems, develop a concept for the design, and show ways to improve efficiency by aggregating network interface channels;

− applying the principle of remote access to the system’s nodes memory of the InfiniBand technology to establish direct data interchange between the RAM of each of the nodes of the multiprocessor system to increase the computational speed and reduce the load on the channels that connect those nodes.

Reasonableness and reliability of the thesis research results are determined by their correlation with the results of other authors using alternative research tools, by the fact that to obtain the author's influences, reliable initial data were used, processed using reliable and tested scientific methods, the consistency, and logicality of the formulation of research tasks, a methodically correct plan of its implementation, implementation of several results in practice at the corporate and regional level, in the educational process, as well as their approval by the expert

community, which is confirmed by comprehensive testing of the thesis provisions at scientific conferences and the publication of the results in peer-reviewed papers.

The thesis research develops the principles of the modern digital economy based on the blockchain and the option approach and improves the structures and network features of multiprocessor computing systems to successfully solve applied problems of the digital economy, designed for the significant expenditure of processing time.

The research object was selected information processes in applied problems of the digital economy based on the blockchain and the optional approach and in modular multiprocessor computing systems.

The research subject is the concept of managing the digital transformation of applied economic systems based on the development of blockchain technology and an optional approach; a methodology for the design of new modular multiprocessor computing systems based on reorganizing the network interface structure to solve the digital economy problems; methods and algorithms for distributed modeling of applied problems of the digital economy.

Research methods. When writing the thesis, the methodological basis was the application of system analysis, integrated approaches, which are based, on the one hand, on the principles of economic theory, blockchain theory, and options, and on the other, on the conceptual principles of economic and mathematical modeling of processes in the digital economy. For the design and implementation of the aggregation procedure for the network interface channels of a multiprocessor computer system, the fundamental provisions of high-performance computing theories, the operating systems construction, parallel computing, and computing systems were applied. In creating parallel algorithms for solving applied problems of the digital economy, the linear algebra methods, the main provisions of the theory of differential equations, the basic principles of the theory of the difference schemes, and methods of mathematical analysis were useful. A technique for creating mathematical models for solving options valuation problems was based on

approximation features of finite-difference splitting schemes, so implementations were developed based on modular and object-oriented programming theory.

The scientific novelty of the results. By developing theoretical foundations and experimental research and their practical implementation, an important scientific task of developing conceptual and methodological provisions aimed at developing the principles of a modern digital economy based on blockchain and an optional approach. Moreover, improving the structures and network features of multiprocessor computing systems has been completed the successful solution to applied problems of the digital economy, designed for significant processing time.

The most significant scientific results obtained by the author are as follows:

The author's interpretation of the formation of a new external environment of enterprises - the "digital environment" - as a space for the manifestation of the competitive advantages of the digital economy transformation is characterized by clarifying the digitalization impact on the activities of corporate entities.

The author's concept of corporate value management was further developed, considering the influence of digital factors, including radical changes in technological processes, which covers recommendations on new digital value management tools adaptation, allowing for viewing the digital component of the modern markets' growth.

For the first time, a new method of creating a fully scalable, evidence-based, and energy-efficient blockchain has been proposed by a new consensus protocol, sharding, and distributed randomness generation, which differs from the known methods in stability and reliability.

For the first time, a new model for analyzing the blockchain protocols' security based on the segmentation procedure has been developed, which differs in that it allows one to estimate the failure probabilities of one node and then each chain of the blockchain based on the hypergeometric and binomial distributions.

For the first time, an approach was proposed that determines the conditions by which the chains of blocks formed based on the segmentation procedure retain the failure probability less than a given threshold, which, unlike the available

approach, allows computing the average number of years during which the blockchain network can fail, which, in turn, allows achieving a given level of security (in terms of the number of years before failure) to compute the minimum size of the blockchain network.

For the first time, new option creation of real options in the digital economy has been developed, which, in contrast to the available ones, allows evaluating the business models of corporate governance, considering target orientation towards the generation of digital assets.

For the first time, a new approach has been developed for evaluating options based on parallel algorithms of the Monte Carlo method, which differs from the available ones instability for any input data, has the maximum similar form, and, therefore, the minimum implementation time on parallel computing devices.

For the first time, a module of a multiprocessor computing system with expandable computational domains has been developed, which is distinguished by a two-level procedure for aggregating network interface channels with such advantages as low latency and high performance, which in turn created opportunities for solving applied problems of the digital economy designed for such a computational domain.

The numerical-analytical method for solving partial differential equations based on modern parallel computing technologies has been further developed to determine the options pricing, which allowed, in comparison with the traditional approach, to increase the accuracy and achieve high efficiency of computations reducing the processing time.

The research's practical significance lies in the fact that the approaches in the thesis research to the digital economy foundations based on the development of the blockchain and the optional approach can be implemented and adapted in the form of specific methods in any organization. The proposed new methods for organizing blockchain technology can be applied in various areas of the digital economy. The new methods for options pricing developed in the thesis will allow obtaining accurate and reliable information regarding the financial assets of enterprises.

The multiprocessor system with expandable computational domains proposed in the thesis allows increasing efficiency and accuracy of economic and mathematical modeling when applied to solving applied economics problems. Developed hardware and software tools, mathematical models, algorithms, and methods are implemented as industrial designs and software products.

The experience of researching the design and application of multiprocessor computing systems is reflected in the monograph "Structural transformations and problems of information economy forms," designed to train specialists in applied economics and information technologies.

Researcher's personal contribution. The dissertation is an independent scientific research, which includes the author's development of theoretical foundations and methodological provisions, and scientific and practical recommendations for managing the digital transformation of applied economic systems based on the development of blockchain technology and the option approach; improving the structure and increasing the efficiency of multiprocessing systems adapted to the tasks of the studied class of the digital economy, and the implementation on their basis of numerical-analytical algorithms and methods that can increase the speed, accuracy, and reliability of experimental data processing. Scientific provisions, conclusions and recommendations that are submitted for defense are received by the author personally. Of the scientific papers that are published in co-authorship, only those ideas that are the result of the applicant's own research are investigated in the dissertation.

Approbation of dissertation results. The main provisions, conclusions and recommendations of the dissertation were reported and approved at scientific and practical conferences: 'Competitive access algorithms analysis of blockchain technology' at XIII International Scientific Practical Conference (Kharkiv, Ukraine, 2021), 'Some Aspects of Innovative Blockchain Technology Application' at XII International Scientific and Practical Conference (Bratislava, 2020), 'Numerical and Analitical Schemes of Distributed Modeling of Economic Systems' and 'Parallel Implementation of the Combined Algorithm of the Branch

and Bound Method' at III International Scientific and Practical Conference (Dnipro 2019, 'Blockchain technology as a means of improving enterprise efficiency' X international scientific and practical conference on banking economy (Pinsk, Belarus, 2019), 'Problem of computing capabilities expansion of modular multiprocessor computing systems' at XI International Conference on Strategy of Quality in Industry and Education, (Varna, Bulgaria, 2018).

Publications: The main results of the dissertation were reflected in 29 scientific papers, including 6 papers published in Scopus-indexed journals, 6 papers accepted and ready for publishing, 8 publications in scientific journals, 3 monographs, 6 publications - based on the materials of the scientific-practical conference.

Structure and scope of dissertation. The dissertation has an introduction, six sections, conclusions, a bibliography used. The total volume of the dissertation is 190 pages.

The main essence of the dissertation

First chapter demonstrates that the digital economy reveals many opportunities, from remittances and payments to smart contracts and document reconciliation. It noted that its strengths, such as lower costs, increased security, and transparency of transactions, attracted the attention of the banking sector.

The author's definition of the digital economy, digital technologies, and "end-to-end" digital technologies has been introduced to understand the problems under consideration.

In this regard, this approach concluded that the digital economy is distinguished by several subtleties associated with insufficient knowledge, understanding of technical implementation, and flexibility. Therefore, it is too early to mention a complete change in the current appearance of enterprises under its influence. However, the indisputable fact is that the digital approach can transform their internal structure. However, for the digital economy to become widespread, it is necessary to address legal legitimacy, regulation, technical viability, standardization, and widespread adoption.

To fully understand the features and problems of introducing the digital economy, this thesis chapter analyzes and highlights the problems of raising such technology in modern society's most relevant areas: document management, logistics, and banking.

That allowed identifying the most promising and dynamically developing digital economy technologies.

Thus, it has been shown that blockchain technology is a distributed, decentralized, encrypted database wherein every committed transaction is recorded and becomes known to all network participants. Data on completed transactions are stored in a specific order and form an unchanging sequence of related blocks. This thesis chapter developed the author's development concept of the basic principles of blockchain technology functioning, indicating the main directions of application and prospects for such technology development these days.

So, it is noted that the efforts of many developers, for instance, blockchain technologies, are primarily aimed at solving documentation problems. Here is a new way of formation, application, storage of documents, and control. As one of the main components of the digital economy, Blockchain technology seeks to change the way of establishing the authenticity of documents: from relying on a trusted third party to an establishing authenticity method. Of course, the approach is of undoubted interest and the prospect of implementation.

Blockchain technologies in supply chains are also of undoubted interest. That is because logistics at the current stage of development is one of the biggest challenges for modern companies. The industry seeks new technologies to improve available processes, reduce costs, and increase transparency in the supply chain. Thus blockchain technology offers a solution to most of the current problems.

As for the blockchain technology application in the banking sector, among modern experts analyzing the possibilities of blockchain applications in the banking sector, there is an opinion that this technology can completely transform the banks' structure. Moreover, soon it becomes radically different from what we have now. Avoiding the mediation of third parties in various transactions can make

a huge layer of banking services useless. However, as shown in this thesis chapter, implementing this idea is far from seamless and has many subtleties that must be properly identified and processed.

In addition, this thesis chapter highlights the fundamental features of the option technologies development as one of the most important components of the digital economy. Thus, the options analysis as the most flexible and practical financial instrument of the digital economy. This thesis chapter highlights the main provisions of tactics and strategies in solving the problem of options pricing. Meanwhile, a new author's classification of options contracts is presented, which allows for determining option contract application, use, and development. At the same time, the analysis of the problem of assessing the price of options contracts showed the relevance of developing new mathematical methods for their reliable and accurate assessment.

Finally, the above studies allow observing that the prospects for the digital economy development are endless: from the money transfer to the music transfer, from the large state projects approval to land regulation innovations, from transparent monitoring of the public funds spending to the salaries receipt regulation of officials and deputies. The approach application is multifaceted, and it is generally difficult to guess where humanity will find digital technology applications in the foreseeable future.

On the other hand, the studies showed that one of the main problems of the technology is the peculiarities of the modeling process, both machine and mathematical. Thus, it is shown that it is necessary to use powerful computer technology and high-performance ones both for maintenance and for solving modeling problems.

At the same time, increasing the computing resources efficiency is doubtless to anyone, and today they are relevant. Moreover, it was shown that parallel computing is the most promising approach to increasing the speed and efficiency of computing facilities.

Summing up the previous remarks, we can conclude that parallel computing, a promising and attractive field of computing technology application, is a complex scientific and technical problem. At the same time, the difficulties that arise during the parallel computing systems development with given features, as a rule, are primary and require deep study and research. Current practice shows that distributed (parallel) computer modeling can be implemented by the entire spectrum of modern computing technology: supercomputers, cluster computing systems, local and global networks, etc. Additionally, the distributed modeling allows processing problems of the digital economy, which solution requires significant processor time, to integrate mathematical models to work on different computing systems.

The second chapter represents that the advent of such a concept as the "digital economy" should be attributed to the number of significant modern changes in the economic environment. It is noted that such an approach in the development of the contemporary economy integrates the changes that have occurred are occurring and will continue to occur in the economic space under the decisive influence of information and communication technologies. It is emphasized that at present, the digital economy is interpreted as an actual trend in the development of modern society, business, industrial production, government, trade and services, and the life of people. The formation of the global digital space is becoming the next stage of development in the chain of "new industrialization - digitalization." It is caused by the need to ensure the technological leadership of subjects and states based on information and communication technologies. The modernization of traditional manufacturing industries accompanies these processes.

The chapter establishes that changes in the economic structure are necessary for the digitalization context in terms of the mechanisms' formation for cross-industry interactions and corresponding new business models for creating added value via digital resources and end-to-end digital processes in cross-industry transitions and cooperation.

It is emphasized that the priority in identifying factors influencing the formation of the digital economy belongs to modern information technologies and the analysis of large amounts of information.

In this regard, the dynamics of information technologies in the business sector were assessed, which allowed forming and substantiating the need to develop new software and analytical tool for enterprises and corporate entities operating in the digital economy.

Thus, the global digital space impact on the digital economy transformation is apparent and confirmed by research in this thesis chapter. Further research is aimed at examining specific technologies of the digital economy.

Further research showed that blockchain technology is one of the main directions for developing the digital economy. It opens up a massive range of opportunities, from money transfers and payments to smart contracts and document reconciliation. Its strengths, such as lower costs, improved security, and transparency of transactions, drew the attention of various economic sectors.

The conducted analytical review showed that the choice of tfunds'logy reflects the blockchain funds' competitiveness. It was revealed that approaches to blockchain technology can be implemented according to two central schemes: "technology first, problem second" or "problem first, technology second." However, studies have shown that enterprises with extensive experience implementing blockchain technology tools tend to operate according to the second scheme. In this case, the corresponding problem is considered, then rectifying the problem solution via the blockchain. Some researchers note that this is the most effective approach.

With this respect, an analysis of software platforms for blockchain construction was carried out. Given the availability of several central blockchain cores, based on which available networks are built, it is convenient to call them exactly technologies. At the same time, it is shown that it is advisable to use ready-made software platforms.

The analysis showed that the platform for building Ethereum decentralized applications is the most secure for storing data since it takes centuries to crack the Ethereum secret key. Thanks to this, a messenger based on this technology eliminates the need to implement two types of chats - secret and cloud. In addition, the non-interference of third parties and malefactors in secret correspondence is guaranteed. Users can access previously sent and received files and messages from any device in real-time. This function is beneficial in case of loss or change of smartphone or when using the same account on different devices.

Considering the above, on the one hand, and in order to identify the main features of the blockchain functioning, on the other hand, in this thesis chapter, a project was developed to form a specific blockchain. To do this project, Python version 3.7.1 was chosen. Its convenience lies in the fact that it has several libraries for implementing the essential functions of the blockchain. For instance, block hashing was done using the hashlib library. Furthermore, the blocks structure itself was advantageous to set as json objects, for which the json library was used.

A methodology for building a blockchain got developed, which proposed to divide the software development process into three stages:

- blockchain building;
- API integration formation;
- other blocks interact with the built blockchain.

A detailed analysis of each stage was carried out.

This chapter shows that one of the essential features of the software is checking its integrity. Such verification is fundamentally crucial for the blockchain transformation into an infrastructure technology for blockchain. Thus, the problem of checking the blockchain integrity was solved. Its essence is as follows: for each block, starting from the second, the previous block is determined; for the previous block, the hash is computed and compared with the "hash" field of the current block. If they match, then the block successfully passes the integrity check.

The conducted research revealed the main shortcomings and contradictions of decentralized data storage in the blockchain system. The next chapter of the thesis exposes the elimination of the identified weaknesses and contradictions.

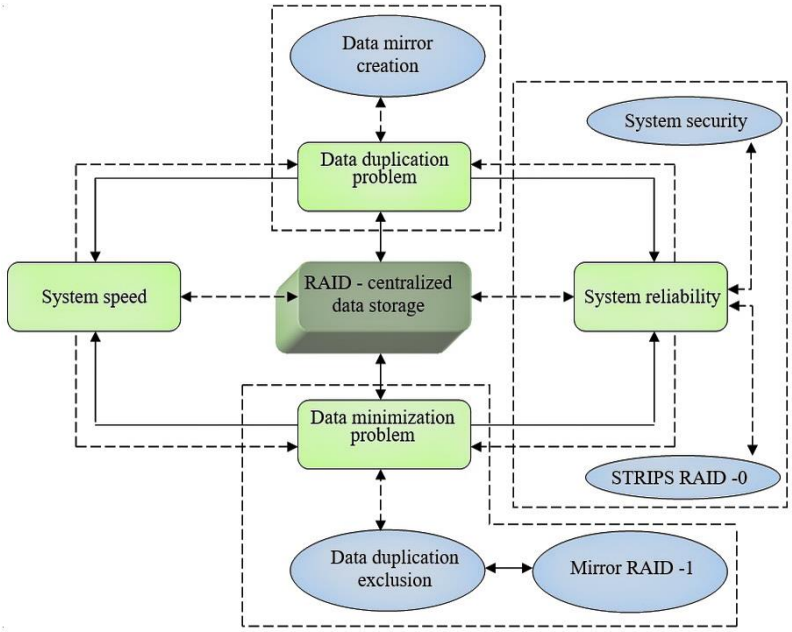

Figure 1. Contradiction scheme for decentralized data storage in blockchain system
(Source: *Authors' elaboration*)

The third chapter proposes and explores a new blockchain system that operates on a linearly scalable consensus mechanism with a selection method that confirms the shard by stock voting and has scalable random generation using *VRF* (*Verifiable Random Function*) and *VDF* (*Verifiable Delay Function*) functions.

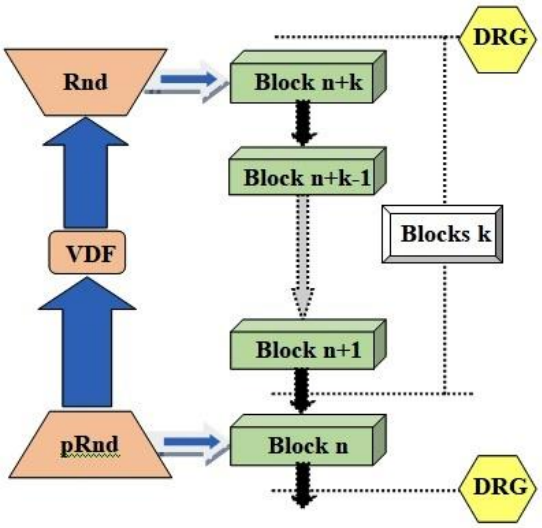

Figure 2. A mechanism for delaying the final randomness detection by VDF
(Source: *Authors' elaboration*)

The new system is based on analyzing available consensus mechanisms, sharding, and distributed randomness generation. The proposed approach allows the development of a blockchain with the following advantages: full scalability, security, energy efficiency, and fast consensus.

The shortcomings analysis of available systems for the blockchain demonstrated that the proposed sharding method performs network connection and transaction verification and reveals the blockchain state. The proposed consensus mechanism showed that the acceptance threshold is low enough for small validators to participate in the network and receive rewards. The sharding process covered in this thesis chapter is safe due to distributed randomness (*DRG*), unpredictable, impartial, and proven. The network is constantly overloaded to prevent slow adaptive Byzantine malicious validators. Unlike other blockchains built on sharding and require a *PoW*-type transaction verification and confirmation model to select validators, the proposed consensus is based on the PoS model and, therefore, more energy-efficient. Consensus is achieved by the linearly scalable *BFT* algorithm, which is more of a *PBFT*. A scalable and secure new blockchain system is obtained by introducing innovations at the protocol and network levels that can support the decentralized economy.

Creating the proposed blockchain improves the available mechanisms of blockchain functioning and has practical value for application in various digital economy sectors.

In addition, this thesis chapter represents a new model for analyzing the security of blockchain protocols based on a segmentation process. To assess the single shard reliability or blockchain failure as a whole, based on the hypergeometric and binomial probability distributions, the probability failure boundaries are determined.

Further research aimed to determine the conditions that must be met for the blockchain-based on segmentation process to keep the failure probability below a given threshold. Considering the failure probability threshold, the proposed procedure for computing the average number of years during which the network

can fail. Thus, to achieve a given level of security (in terms of the number of years before failure), an approach was developed, allowing to determine the minimum shard size that should be formed using blockchain protocols based on the segmentation process.

The fourth chapter shows that the expansion of possibilities in the design of computer technology was always a factor influencing the development of information technology in general and the digital economy in particular. It is shown that the importance of computational tools is of particular importance in solving problems of the digital economy since the study of many processes often requires data on such phenomena, which in real conditions are very complex and costly. In some cases, it is simply impossible. A specific feature of all new computing systems is the possibility of simultaneous or parallel use of a certain number of processors for information processing. So, the common name for them became parallel. Creating such systems determined one of the most important ways to increase the speed of solving complex and large-scale computations.

Today, special interest in building tools is due to standard publicly available technologies and components. In particular, modular computing systems designed with blade technologies (blades systems) became widespread. The need for the development and construction of multiprocessor computing systems is justified in the publications of many scientists. Under such conditions, the topic of designing modular multiprocessor systems today is relevant, interesting, and at the stage of its active development. It is also obvious that highly efficient clusters found a rational way of performing many tasks. It is also necessary to determine that a new qualitative stage in modular multiprocessor systems is associated with modern network technologies. Today the problem of choosing and analyzing network technologies for modular multiprocessor cluster systems has not been fully resolved.

On the other hand, this thesis chapter demonstrates that it is possible to design both homogeneous and heterogeneous multiprocessor systems under the necessary conditions. In addition, considering the modularity of the proposed

system, in general, based on the developed system, it is possible to build computing farms based on graphic processors.

Furthermore, we note that today the blockchain environment software can detect all devices installed on a particular multiprocessor module. Therefore, a situation often arises when in order to achieve a certain goal, it is necessary to use both the *CPU* and video cards. That phenomenon can be quite common. For instance, one of the most common software tools for implementing blockchain tasks is the *NiceHashMiner*, right at the beginning of work, which offers a choice of several devices suitable for this purpose and roughly estimates the hash rate of each. The cost of work in real currency is also displayed there, considering the current exchange rate. So, for this kind of task, one can use technical implementations highlighted in this thesis chapter.

Considering the above, it can be argued that parallel computing systems are one of the strategic directions for digital economy development. That can be explained by the constant growth in the number of applied problems for which solution the capabilities of current computing facilities are not enough. Among such problems, first of all, are the problems of modeling both blockchain technologies and options pricing. However, such problems are also encountered in numerical modeling of pattern recognition processes, optimization computations with many parameters, etc. Obviously, by highly efficient clusters, a successful way was found to perform urgent tasks of a wide class. Therefore, this thesis chapter examines constructing a multiprocessor system with an expandable computational domain.

Nowadays, special interest in the construction of multiprocessor parallel computing systems (clusters) is due to the possibility of applying publicly available components and technologies for this matter. Substantial competition between manufacturers of computer technology leads to the fact that the prices of its parts are decreasing quite dynamically. The same goes for the release of new models of computers. Despite the variety and scale of production of current information and computing devices, it is safe to say that by using standard

components, it is possible to build powerful computing systems in a very short time and with the fullest possible consideration of the needs of various users. Moreover, depending on the type of tasks and the budget size allocated for the project, multiple options for the operating system configuration are possible.

An analysis of approaches to the multiprocessor systems design showed that computer manufacturers offer devices based on blade technologies. Under these circumstances, constructing a multiprocessor system based on blade servers results in a complete chassis equipped with the necessary controls and network interface. Let us describe some of the main advantages of such design solutions: blade systems are more compact and easier to maintain, and their design features allow convenient configuration formation.

Due to the increased supply and demand for blade configurations, it was decided to design a blade-cluster computing complex to solve the class's problems under study. However, here the problem arises of determining the number of blades in the formed cluster system. Some developers of such systems believe that the number of computational nodes entirely depends on the class such systems solve. Herein, the computations are based on partial differential equations. Nowadays, such equations represent one of the branches of numerical analysis that is developing very intensively. Considering the described circumstances in building the cluster, it was decided to limit ourselves to six nodes. On the one hand, it is always possible to extend the cluster if necessary, and on the other hand, using a smaller number of nodes can reduce the efficiency of its operation. Finally, given available funding problems, this choice can be considered optimal.

In constructing a multiprocessor system, its design is of fundamental importance. At this stage, it is necessary to envisage the possibility of expanding the system or its modification in the future. The most successful constructive solution for the cluster is its position in the rack. That is appropriate even for a small cluster system, and the above design requires no high costs.

No less important than the racks is the choice of the form factor of the computing nodes. Today, there are several traditional solutions for this. The

multiprocessor system considered in this thesis' chapter is designed based on the blade technologies. At the same time, it is known that the use of racks for blade servers (blades) is recognized as the most compact and convenient in the successful conduct of routine maintenance and repair since it provides unhindered access to any parts of the cluster. Besides, the described design meets the needs of the future development of the cluster since it allows easily replacing any system components with new analogs: powerful processors, larger memory, new disks, new motherboards, etc.

Considering the described features, a constructive solution was chosen for the cluster in the form of a single housing with a center of computing rack. The developed multiprocessor system basis is densely packed systems with blade-type processors built in a rack with nodes, equipment, network interface means, controls for system internal networks, etc.

Each blade of the modular system runs a standard operating system. The power and composition of the nodes can be different within the same system. In particular, a homogeneous cluster was designed, and the interaction between the nodes occurs through the specialized function libraries. The *MPI* standard with mpich-1 open base implementation was chosen as the software toolkit for parallel computing.

The developed modular computing system described in this chapter has the following dimensions: 19" wide, 10.9" long, and 9" deep. The total weight of the devices is about 7 kg.

It was also determined that a new qualitative stage in developing multiprocessor computing systems is applying new modern network technologies. That can be explained by the significant differences between the cluster computing system network and the workstation network. Although constructing a cluster requires ordinary network cards and switches for organizing a network of workstations, a cluster computing system has one fundamental feature. Thus, the computing system network is not intended for connecting computers but for connecting computing processes. Then, the higher the network bandwidth of the

system, the faster the user-defined parallel tasks execute. So, the technical features of a computer network are of paramount importance when it comes to multiprocessor computing systems. Considering those above, it was decided to use InfiniBand network interface technology.

So, the *InfiniBand* standard organizes data interchange between nodes of a multiprocessor system. Besides, the developed system has next fundamental features: processors' network booting, *VLAN* mode maintaining, a mechanism for booking key module components, a specially designed mode of data interchange between system nodes in the InfiniBand switch network.

The listed features of the developed system allowed improving it with certain differences from available systems, namely:

- firstly, owing to the InfiniBand technology implementation, the following advantages were achieved: low latency and high performance that allows solving problems where an extended computational domain is provided;

- secondly, the ability to change the configuration of the system's local networks via the control panel or *WEB*-interface, adapting their structures to solving problems of any type;

- thirdly, based on the *RDMA* principle of InfiniBand technology, direct data interchange between the *RAM* of the multiprocessor system nodes is run, increases the speed of computations, and provides high-speed access to the memory of its slave-nodes, as well as data interchange between them, unloading the *CPU* system during data interchange and reducing the load on the channel that passes between the computing system's nodes;

- fourthly, such adapters as *ConnectX* creates fundamentally new opportunities for the "connectivity" of such a system with other computing environments; in particular, it allows unloading the central processor (by servicing InfiniBand traffic) and, as a result, increase the efficiency of the entire *MCS*;

- fifthly, thanks to the modular construction principle, to simplify the design processes, build-up or replace the failed computing nodes, and, in general, operation of the entire designed system.

The fifth chapter focuses on the study of real options. Thus, it is noted that a real option is the ability to make flexible decisions under uncertain conditions. Stuart Myers first introduced the "real option" term in 1977. He offered to apply options pricing theory to the valuation of non-financial or "real" investments, including new information and flexibility.

At present, interest in the concept and technique of using real options increased significantly. Attention started as a potentially important tool for assessing and developing a strategy, first in the oil and gas sector and then in other areas related to corporate investments.

It is shown that the development of modern data processing models, including Big data, suggests that there are new opportunities for applying the real options method for the digital component of corporate management due to several properties of both the options themselves and the value-oriented approach to corporate management in general.

In this regard, to reflect the generating income processes n the digital sphere based on applying the real options method, the main aspects of the sound value decisions formation in enterprise management are highlighted. Based on the proposed approach, real options application possibilities for the economy under digitalization and business processes based on digital platforms are determined.

The analysis of the economy operating in the digital environment was carried out. Meanwhile, the main requirements of economic digitalization are highlighted.

For an economy operating in a digital environment and, above all, based on digital platforms, the main requirements for digitalizing real options applications are highlighted. Here the focus is on the *dematerialization of assets*. It is shown that the dematerialization of assets should be interpreted as an evolutionary process of the assets structure transformation of a company operating in digital transformation, when intellectual capital is represented by intangible assets, namely, information systems, software, and information as databases of different

formats and security. The dematerialization of assets objectively accompanies the implementation of the digital platform as a business model for digital companies.

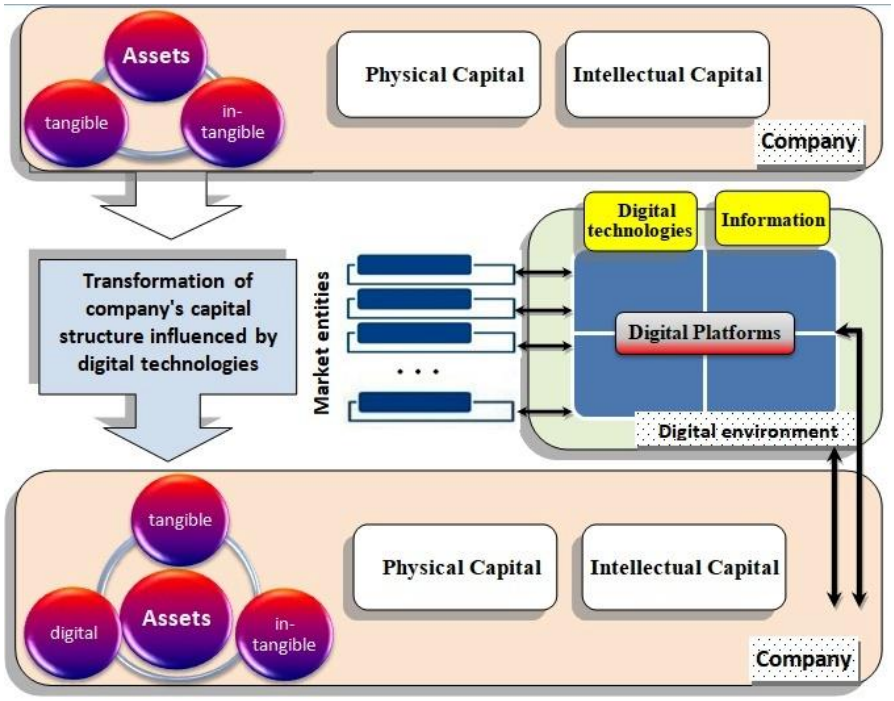

Figure 3. Company's capital structure transformation, including assets dematerialization
(Source: *Authors' elaboration*)

In order to develop option structures for new types of options operating in the digital economy, a comparative analysis of the classic option and the new option was carried out. Based on this approach, new option structures were developed: *License* option for the digital platform for both the seller and the buyer; *PR* option for advertising contracts for a digital platform; *Loyalty* option, and *Digi-Smart* option.

Figure 4. Types of options
(Source: *Authors' elaboration*)

The studies conducted allowed establishing that a real option in the digital economy in one of three varieties (an option on a digital asset, an option on a digital income, or an option on a digital income based on a digital asset) allowed to more accurately reflect the generating income processes in the digital economy and allowing to form reasonable value-based solutions in corporate management, including the digital economy realities.

Based on the research carried out in the second and third chapters of the thesis, there was justified the introduction of a new type of option, the *Digi-smart* option implemented based on blockchain technology, including smart contracts capabilities integrated into the corporate strategy of a digital company as a base element.

The sixth chapter sees the trade is the economy's driving force, and with its digital version development, the options pricing problem becomes more than urgent. In addition to forwarding deals to buy or sell common stocks, there are options contracts for bonds, commodities, stock indices, foreign currencies, and the like.

Note that it is profitable for an investor to buy a *CALL* option if one expects an increase in the price of securities or buy a *PUT* option if one expects a decline in the rate since an increase in the strike price and its current market price of the asset lead to a rise in the prices of *CALL* options and a fall in prices for *PUT* options. And with an increase in price volatility in the market, the options price of both types increases, since the greater the price fluctuations, the more uncertain the future market situation, i.e., the more risky options' sales.

Thus, it becomes obvious that volatility needs to be computed if a forecast is required as to whether the price will rise or drop. In addition, there is historical and latent, also called expected volatility. Historical volatility is used to calculate fair prices, while hidden volatility plots the volatility curve and smile surface.

Thus, the pricing options problem in the digital economy becomes extremely important. At the same time, there are a significant number of options pricing

models. Therefore, this thesis chapter analyses available methods for options pricing. The classification of such methods was done for the first time. It is shown that the methods for options pricing can be divided into three groups: analytical, boundary methods for solving partial differential equations, and statistical. The Analysis allowed the development of the most promising approaches to the development of the new methods of options pricing.

It is shown that the *Black-Scholes-Merton* model can be distinguished among the mentioned analytical methods. The thesis chapter mainly focuses on Merton's approach as an improved version of the *Black-Scholes* model. For the first time, new results were obtained by Merton, which essentially meant the dividend should be interpreted as a drop in the share price at the time of the "no dividend" date. In this regard, such a model began to be called *Black-Scholes-Merton* model.

It is noted that one of the significant drawbacks of such models is the fact that the volatility in such equations cannot be measured directly. It can be determined using statistical samples and variance computation equations from historical data. Alternatively, as is usually the case in practice, introduce the implied volatility concept. However, that does not allow for absolute accuracy to determine the volatility value for computation by the *Black-Scholes-Merton* equation, leading to inaccuracies in determining the options' exchange prices.

Let us point out one more major drawback of the given models. It lies in the fact that this approach is designed to determine the European options prices, which practically are unavailable in reality. An approximation determines the American option price, i.e., *Black's approximation* is widely known as it works well in most cases. However, it is only applicable if the option contracts are used rationally.

The above analysis allows noting that analytical methods, at one time, identified a certain breakthrough in the options pricing. However, the unforeseen change in market volatility backfired in financial markets. Some experts call analytical mathematical models a "dangerous invention" that unnecessarily simplified such a complex issue as asset valuation. The 1998 crisis showed that

great volatility changes occur more often than anticipated, and therefore all assets have to be revalued with new ratios. Experts note that this situation arose due to a significantly simplified mathematical model.

The above comparative analysis of the development of the analytical method demonstrated that they are at the stage of their development and improvement.

Applying boundary models for solving partial differential equations in the option pricing problem showed the following. Analytical solutions to boundary value problems apply to fairly simple mathematical models. That is explained by the problem of integrating such models when in analytic quadratures, the solution can be found for a strictly narrow class of integrands. For more complex and practical problems, numerical methods are used. Such methods' essence is to apply explicit or implicit schemes. However, such methods cannot be parallelized to solve multiprocessor computing systems due to their recurrence.

In this regard, this thesis chapter shows that the numerical-analytical approach is promising in multiprocessor systems today.

So, it is shown that there are certain trends in the development of numerical-analytical methods with a complex logical structure today. However, compared to piecewise-difference methods, they have a higher order of accuracy and the possibility of making algorithms with adaptation by approximation orders. This approach is somewhat cumbersome from a computational point of view, but it provides a benchmark for comparison with other practical methods. Nevertheless, although computational experiments are run on a multiprocessor system, it can be argued that the circumstance that hindered the numerical-analytical approach development is losing relevance nowadays. Hence, the thesis further promoted the idea of developing schemes of a higher order of accuracy based on a numerical-analytical approach to solve a wide class of problems under study.

Among the statistical options pricing models, the binomial model can be distinguished as the most simple and intuitive one for obtaining a general picture of the statistical approach. The binomial model was made for the discrete single-period case, where the asset price movement corresponds to a stationary binomial

stochastic process, i.e., at the end of the period, it can be greater or less than the initial one. The binomial model and its modifications are used for European, American, and Asian options' pricing.

Binomial models are very easy to understand and implement in practice. Such models provide a logical and clear assessment of the option contract. Yet, one of their significant drawbacks is an extremely rough options pricing when solving a practical range of problems.

The binomial approach essence represents the evolution of the price of the underlying asset of an option as a binary tree of all possible prices with a uniform division of the time interval from today. Herein, it is assumed that the price can only rise or drop by a fixed number with the corresponding probabilities at each step. In other words, the tree's root is the current price of the underlying asset; each level represents all possible prices at a given time. Each node has two slave nodes with values; multipliers of price movement are up and down, respectively, in a single step.

Under such circumstances, it becomes clear that the underlying asset's price changes several times over the period. Applying such trees in practice usually takes at least 30 intervals of length Δt. At each moment, the tree is divided into two possible options, then the number of all possible paths (trajectories) that the investor must consider is 230, i.e., about a billion. On the one hand, quite cumbersome computations are obtained here. On the other hand, it is obvious that parallelizing computations due to recurrence becomes impossible.

This thesis chapter illustrates that among the various numerical methods in economic and mathematical computations in recent years, one can note the revival of such a method as the *Monte Carlo* method. The Analysis of such methods showed that there are solution methods for some classes of partial differential equations, integral equations, eigenvalue problems, and systems of linear and algebraic equations. Those circumstances formed the basis for new approach development to the options pricing based on *Monte Carlo* methods.

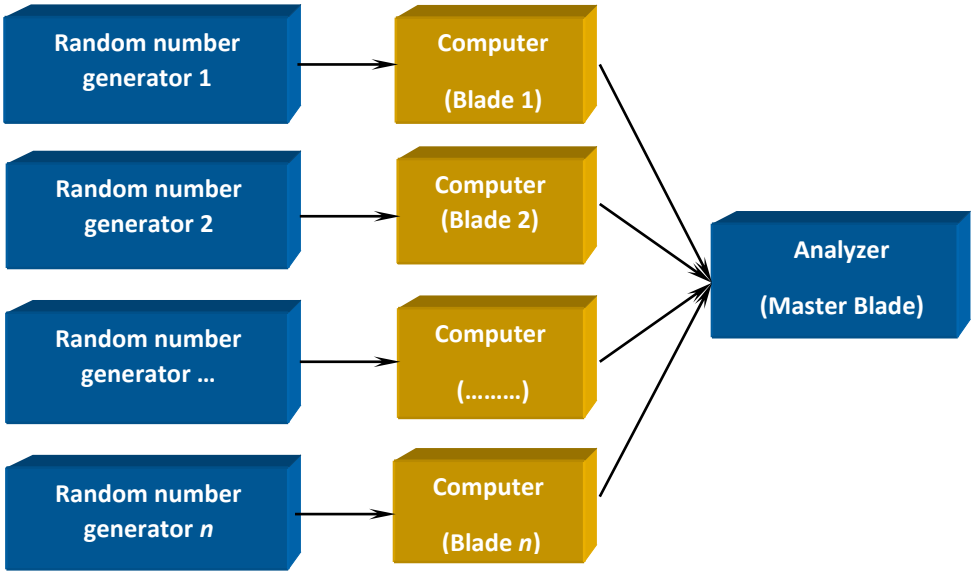

Figure 5. Modified algorithm for parallel computations by the Monte Carlo method
(Source: *Authors' elaboration*)

The main feature of the proposed approach is modular multiprocessor systems, which design features are outlined in the fourth chapter of the thesis. The experience of operating the first parallel systems showed that it is necessary to radically change the structure of numerical methods for their efficient operation. In this regard, corresponding distributed algorithms were developed; features of modeling applied problems based on multiprocessor systems were discovered and shown.

Recently, one can note the revival of the *Monte Carlo* method. That is because the method is ideal for a clustered multiprocessor system. Moreover, the more processors there are in the cluster, the more efficiently the problem is solved. The *Monte Carlo* method has made and continues to significantly impact the development of computational mathematics methods and related applications of the digital economy. First of all, its application is justified to the solution of such problems that admit a probabilistic description. That is explained both by the naturalness of obtaining a solution with a certain given probability in problems with probabilistic content and by a significant simplification of the decoupling

procedure. Under such circumstances, this thesis chapter highlights the cluster problems of applying the *Monte Carlo* method to solving the digital economy's problems.

The method's slow convergence is its disadvantage. However, the studies showed that the formation of selective random numbers relative to individual groups could significantly increase the method's accuracy.

In addition, it is shown that the *Monte Carlo* method is quite well adapted to solving multidimensional problems. For instance, applying the usual method of solving systems of linear algebraic equations to compute one unknown value is necessary to determine the rest. The method does not require this, as only one critical system coordinate to be solved is determined each time.

Boundary value problems and problems with initial conditions for linear differential equations are among the most interesting areas of the *Monte Carlo* method application, and that became possible only thanks to the development of modular multiprocessor computing systems. For those reasons, this thesis chapter gives examples of solving the *Neumann* and *Dirichlet* problems by the *Monte Carlo* method. The approach revealed the specifics of options pricing in the digital economy based on the *Monte Carlo* method.

The method application allows taking a fresh look at the parallelization idea of computations and the cluster computing technologies. These studies propose a modified algorithm for parallel computations by the *Monte Carlo* method. Here, each computer has its random number generator. In this case, intermediate computations are run independently on different, separately taken edges of the cluster-"computers," and the results are processed on a separate master-blade-"analyzer." The circumstance eliminates the indispensable router-communicator between random number generator and "computer." Obviously, such a solution allows for speeding up computation process.

It is shown that the developed parallel algorithms of the *Monte Carlo* method are stable for any input data, have the maximum parallel form, and, therefore, the minimum possible implementation on parallel computing devices. If

it is possible to assign one processor to one computational node, it allows carrying out computations in all nodes of the mesh domain in parallel and simultaneously.

Conclusions

The thesis research, as a result of the development of theoretical foundations and experimental research, and their practical implementation, carried out an essential scientific task to develop conceptual and academic, and methodological provisions aimed at developing the principles of the modern digital economy based on the blockchain and the options approach, and improving the structures and network features of multiprocessor computing systems for the successful solution of applied problems of the digital economy, intended for a significant processing time.

At the same time, the following main scientific, theoretical, and applied results were obtained:

1. An analysis of the modern economic development showed that the economy is gradually becoming digital, as new types of payment systems appear, digital financial assets appear, etc. Thus, the digital economy’s popularity refers to the demand of the time. It is shown that digital financial assets have several significant advantages over traditional financial assets: reliable protection with a cryptographic code, anonymity, and the ability to obtain cryptocurrency on one’s own. For instance, the blockchain technology with the distributed database among the participants makes this system's fraud significantly more complicated than traditional payment technologies. Such a system is automatic and self-regulating.

Based on the analysis, the author's interpretation further developed a new external environment formation of enterprises, the "digital environment," as a space for the competitive advantages manifestation of the economy’s digital transformation, characterized by clarification of the digitalization impact on the corporate entities.

2. The research result showed that the digital economy is a new reality, which achievement via digital transformation based on digital platforms is a unique

tool of the digital revolution, which timely and correct application allows corporations to gain competitive advantages already in the new digital economy.

In this regard, the author's concept of corporate value management was further developed, considering the influence of digital factors, including radical changes in technological processes, covering recommendations on the adaptation of new digital value management tools, which allowed taking into account the digital component of the modern market growth.

3. The theoretical principles of distributed ledger technology and their differences from traditional databases are analyzed. A review of blockchain technology was made, and the possibility and feasibility of its application in the digital economy were studied. Algorithms for creating blockchain technology were studied and described, and examples of ready-made solutions for its implementation in the digital economy are given. Considered software tools and features of the development and functioning of blockchain technology.

That allowed the new method development for creating a fully scalable, evidence-based, and energy-efficient blockchain via a new consensus protocol, sharding, and distributed randomness generation, which differs from the known methods in terms of stability and reliability. The proposed methods for creating such a blockchain improve the already available mechanisms for blockchain functioning and have practical value in applying a blockchain distribution database for various digital economy needs.

4. For the first time, a new model for analyzing the security of blockchain protocols based on the segmentation procedure was developed to estimate the failure probability of one node and then each chain of the blockchain based on hypergeometric and binomial distributions.

5. A new approach is proposed that determines the conditions by which the chains of blocks formed based on the segmentation procedure retain the probability of failure less than a given threshold, which, in contrast to the available approach, allows computing the average number of years when the blockchain network may

fail. This, in turn, allows computing the minimum size of the blockchain network to achieve a given level of security (in terms of several years before failure).

6. It is shown that the digital economy created a special tool, a smart contract allows the formalization of contractual relations between participants in digital transactions.

That allowed the development of new author's option constructions of real options in the digital economy, which, in contrast to the available ones, allowed evaluation of the business models of corporate governance, including the target orientation towards the generation of digital assets.

7. A newly refined analysis of the main options pricing models was done. That allowed deriving a new author's concept for classifying methods for determining options pricing, distinguishing a class of promising methods developed accordingly in the thesis.

8. For the first time, a new approach was developed for options pricing based on parallel algorithms of the Monte Carlo method, which differs from the available ones in stability for any input data, having the maximum parallel form and, therefore, the minimum implementation time on parallel computing devices.

9. For the first time, a module of a multiprocessor computing system with expandable computational domains was developed, which is distinguished by a two-level procedure for aggregating network interface channels providing such advantages as low latency and high performance, which in turn created opportunities for solving applied problems of the digital economy designed for such computational domain.

10. The numerical-analytical method for solving partial differential equations based on the modern parallel computing technologies for determining the option price was further developed, which allowed, in comparison with the traditional approach, to increase the accuracy and achieve high efficiency of computations, reducing the processing time.

11. The distributed computing experiments significantly reduced the number of experiments and their implementation due to obtaining the necessary

information via mathematical models of real phenomena and developed software complexes. The created mathematical models, methods, and tools proved in practical implementation in software and industrial designs.

12. The practical implementation of the developed provisions of the economy's digital transformation concept is an important and practically significant task, which solution can contribute to the initiation of digital transformation of social and economic systems and the accelerated formation of the digital economy as a whole.

The approaches to the digital economy foundations development based on the development of the blockchain and the optional approach formulated in the thesis research can be implemented and adapted in the form of specific methods in any organization. The proposed new methods for organizing blockchain technology can be applied in various areas of the digital economy. The new methods for options pricing developed in the thesis allow obtaining accurate and reliable information regarding the financial assets of enterprises.

List of published papers on the dissertation topic

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1. Shvachych G., Moroz B., Khylko M., Sashchyk H., Khylko O. and Busygin V. Mathematical Modeling of the Data Processing Problems of Heat Experiments Based on Multi-Processor Computing Complexes// Inventive Communication and Computational Technologies. ICICCT 2020, Lecture Notes in Networks and Systems, Springer

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