ABSTRACT

For the dissertation titled « Research of fault-tolerance algorithms for reliable information processing» submitted by Mukhit Zhanuzakov Baurzhanovich for the degree of Doctor of Philosophy (PhD) in the educational program 8D06103 – «Computer Science»

Relevance. The increasing complexity of computing systems introduces higher risks of failures. Existing fault-tolerance algorithms often suffer from scalability issues, high computational overhead, or limited adaptability to diverse failure scenarios. This research aims to develop and evaluate algorithms that overcome these limitations, providing robust solutions for reliable information processing.

In the contemporary business environment, the impact of digitalization on enterprises is a transformative force. Integrating digital technologies such as AI, IoT, and data analytics into organizational operations leads to increased efficiency, innovation, and competitiveness. However, this transition is accompanied by obstacles like as data consistency, security, privacy, and the need for a digitally competent workforce. This dissertation attempts to give precise insights into the strategic components of company digitalization through case studies and trend analysis. Understanding these implications is critical for firms crossing the digital frontier and guaranteeing long-term development and competitiveness in today's fast-paced business environment.

The significance of fault-tolerance lies in mitigating the risks associated with system failures, ensuring uninterrupted operations, and safeguarding critical data. Scalability, on the other hand, is crucial for accommodating increased workloads and sustaining optimal performance as enterprises evolve.

When a physical server crashes, applications running on the server become unresponsive. If suspended applications are not quickly restored, the organizations that own them will suffer loss of revenue and reputation. As a result, it is important that applications are built with resiliency in mind to reduce downtime and provide customers with near uninterrupted service. The ability of a system to continue operating in the face of failures or errors determines the crash tolerance of the system. Crash-tolerant methods detect and recover from errors, ensuring that the system continues to function according to its pre-failure behavior.

In this context, incorporating resiliency provisions into server applications is critical to ensure that customers receive a continuous and consistent experience. They must be able to ensure data consistency, prevent data loss, and recover from hardware or software errors.

The aim of this research is to develop and analyze a fault-tolerant information processing methods for distributed systems, in particular enterprise servers, that minimizes performance overhead in failure-free operation while ensuring fast and reliable rollback-recovery algorithms through an optimized checkpointing interval.

Research objectives:

1) Research of fault-tolerance algorithms for reliable information processing

2) Development of a model-based solution and designing an algorithm for computing checkpointing interval for fault-tolerant rollback-recovery algorithm in distributed enterprise systems

3) Designing and implementation of an algorithm for computing checkpointing interval for fault-tolerant rollback-recovery algorithm based on queuing theory

4) Implementation and testing of checkpointing-based rollback-recovery algorithms in a real distributed enterprise systems

Research methods:

Theoretical analysis of fault-tolerance algorithms; enterprise distributed system modelling; designing and testing of rollback-recovery fault-tolerance algorithms.

Research subject:

Fault tolerance algorithms for reliable information processing

Research object:

Distributed systems, enterprise information systems

Scientific novelty of the results obtained:

The novelty of the research work is the development of new and optimized solutions for calculating checkpointing interval for rollback-recovery algorithm. This includes following:

1) First implementation of optimal checkpointing interval for rollback-recovery algorithm based on queuing theory

2) Model-based solution for computing checkpointing interval for fault-tolerant rollback-recovery in distributed enterprise systems

Thesis submitted for defense:

Development of new models and algorithms for calculating optimal checkpointing interval for the fault-tolerant rollback-recovery algorithm in distributed enterprise systems.

Development and application of an algorithm for calculating the optimal checkpointing interval based on queuing theory, which demonstrated a system availability of up to 96.27% and achieved an improvement in overall system efficiency of approximately 3–4% compared to traditional algorithms.

Practical significance of the study: The study develops algorithms for reliable information processing in distributed enterprise systems. It extends existing theories of rollback-recovery mechanisms by introducing approaches for optimal checkpointing interval computation under varying system loads and failure rates. The developed algorithms are implemented and tested in both simulated and realistic the distributed systems, showing the practical significance of the work.

Scientific and technical significance of the study:

The scientific and technical significance of this study lies in the development of advanced fault-tolerance algorithms that enhance the reliability and efficiency of distributed enterprise systems. The research introduces a novel approach to calculating the optimal checkpointing interval based on queuing theory, improving the balance between system performance and recovery speed.

It extends existing theoretical models by incorporating dynamic system parameters such as workload and failure rates. From a technical perspective, the proposed algorithms reduce computational overhead while ensuring rapid rollback-recovery in case of failures. The implemented solutions demonstrate high system availability (up to 96.27%) and improved efficiency compared to traditional methods. Overall, the study provides both theoretical advancements and practical tools for building resilient and scalable digital infrastructures.

Reliability of scientific results:

The reliability of the scientific results obtained in this dissertation is ensured by the integration of theoretical, analytical, and experimental approaches to the study of fault-tolerant information processing in distributed enterprise systems. The research is grounded in established principles of fault tolerance, rollback-recovery mechanisms, and queuing theory, which provides a solid methodological basis for the proposed solutions. Two distinct algorithms—an empirical model-based approach and a queuing-theory-based optimal approach—were developed and systematically evaluated, allowing for comprehensive comparative analysis. The experiments were conducted in both virtualized and physical environments, ensuring that the obtained results are reproducible and reflect realistic operational conditions.

The consistency and validity of the results are confirmed through detailed performance evaluation using key system metrics, including throughput, average service time, system availability, and overall efficiency. The comparative analysis demonstrates stable and predictable behavior of both algorithms under varying system loads and failure scenarios. In particular, the queuing-theory-based algorithm consistently achieved higher availability (up to 96.27%) and efficiency (up to 66.84%), confirming its robustness and effectiveness in balancing system performance and fault tolerance. Repeated experimental runs and controlled parameter variations further support the stability and reliability of the findings.

Additionally, the practical implementation of the proposed algorithms in distributed enterprise environments validates their applicability and effectiveness in real-world scenarios. The results demonstrate that the developed methods ensure rapid recovery, minimize recomputation losses, and maintain service continuity during failures. The inclusion of AI and Big Data elements for enterprise process optimization further strengthens the reliability of the overall approach by extending its applicability beyond traditional fault tolerance. Thus, the combination of theoretical justification, experimental validation, and practical implementation confirms the high reliability and credibility of the scientific results presented in this study.

Relation of the topic to research programs:

This dissertation was carried out as part of the scientific project AP09259208 entitled «Development of a scalable fault-tolerant information system for enterprise digitalization using Big Data technologies» (0121RK00369).

Dissertation structure and contents:

The dissertation consists of an introduction, three main sections, a conclusion, and a bibliography. The total length of the work is 99 pages, including 43 figures, 23 tables, and 40 formulas. The bibliography includes 101 references.

Introduction section determines the relevance of the work and the indicates issues related to the topic. It describes the idea of the work, the goals and objectives of the study, the scientific novelty and practical value of the study and research methods.

The first chapter provides a review of scientific papers and a detailed analysis of fault-tolerance and load-balancing algorithms. It also presents the research gap, introduces the design challenges.

The second chapter describes algorithms for calculating optimal checkpointing interval for rollback-recovery method developed during research. It includes theoretical justification and algorithm design.

The third chapter describes the implementation and testing of the developed algorithms in both simulated and production-like enterprise environment setup. This section provides comparative analysis of traditional algorithms and developed algorithms.

In conclusion section, the main results and conclusions of the dissertation research are outlined.

Publications:

The results of the study were discussed at scientific seminars at the Department of Computer Sciences of Al-Farabi kaznu, as well as at seminars with the participation of a foreign supervisor, and reported at the following international conferences:

1. Balakayeva G., Zhanuzakov M., Darkenbayev D. Comparative analysis of fault tolerance algorithms for fault handling during digitalization of enterprises // Lecture Notes in Networks and Systems. – London: Springer, 2026.

2. Balakayeva G., Nurlybayeva K., Zhanuzakov M. Development of software complex for digitalization of enterprise activities // International Journal of Electrical and Computer Engineering. – 2023. – Vol. 17, No. 12. – P. 315–318.

Articles published in the publication recommended by the Committee for Quality Assurance in the field of Science and Higher Education of the Ministry of Science and Higher Education of the Republic of Kazakhstan:

1. Zhanuzakov M., Balakayeva G., Ezhilchelvan P. Model based solution for computing checkpointing interval for fault-tolerant rollback-recovery in enterprise servers // Journal of Problems in Computer Science and Information Technologies. – 2025. – Vol. 3, No. 1. – P. 25–33. – DOI: 10.26577/jpcsit20253103.

2. Zhanuzakov M., Balakayeva G. A comparative study of load-balancing algorithms for reliability of enterprise information systems // Bulletin of Abai KazNPU. Series of Physical and Mathematical Sciences. – 2024. – Vol. 87, No. 3. – P. 146–153. – DOI: 10.51889/2959-5894.2024.87.3.012.

3. Zhanuzakov M., Balakayeva G. Prediction of employee promotion based on ratings using machine-learning algorithms // Bulletin. Series Physical and Mathematical Sciences. – 2022. – DOI: 10.51889/2022-1.1728-7901.14.

Scientific articles in journals indexed in the Scopus database:

1. Balakayeva G., Zhanuzakov M., Kalmenova G. Development of a digital employee rating evaluation system (DERES) based on machine learning algorithms and 360-degree method // Journal of Intelligent Systems. – 2023. – Vol. 32, No. 1. – Art. 20230008. – DOI: 10.1515/jisys-2023-0008.

2. Balakayeva G., Zhanuzakov M., Zhapbasbayev U., Nurlybayeva K. An

intelligent enterprise system with processing and verification of business documents using big data and AI // Journal of Intelligent Systems. – 2025. – Vol. 34, No. 1. – Art. 20240446. – DOI: 10.1515/jisys-2024-0446.

3. Balakayeva G., Darkenbayev D., Zhanuzakov M. Development of a software system for predicting employee ratings // Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska. – 2023. – Vol. 13, No. 3. – P. 121–124. – DOI: 10.35784/iapgos.3723.