

ҚАЗАҚСТАН РЕСПУБЛИКАСЫНЫҢ ҒЫЛЫМ ЖӘНЕ ЖОҒАРЫ БІЛІМ МИНИСТРЛІГІ
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MINISTRY OF SCIENCE AND HIGHER EDUCATION OF THE REPUBLIC OF KAZAKHSTAN



**ХАЛЫҚАРАЛЫҚ АҚПАРАТТЫҚ ЖӘНЕ
КОММУНИКАЦИЯЛЫҚ ТЕХНОЛОГИЯЛАР
ЖУРНАЛЫ**

**МЕЖДУНАРОДНЫЙ ЖУРНАЛ
ИНФОРМАЦИОННЫХ И
КОММУНИКАЦИОННЫХ ТЕХНОЛОГИЙ**

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МАЗМҰНЫ

ӘЛЕУМЕТТІК-ЭКОНОМИКАЛЫҚ ЖҮЙЕЛЕРДІ ДАМУДАҒЫ ЦИФРЛЫҚ ТЕХНОЛОГИЯЛАР

М.М. Жалғасова, К.В. Колесникова

ІСВ ҚҰЗЫРЕТТІЛІК МОДЕЛІН ЖОБАЛАРДЫ БАСҚАРУДЫҢ САЛАЛЫҚ ҚАЖЕТТІЛІКТЕРІНЕ
БЕЙІМДЕУ.....8

Г. Мауина, А. Найзағараева, Э. Тулегенова, Б. Жүсіпбек, М.У. Худойберганов

АУЫЛШАРУАШЫЛЫҚ РЕСУРСТАРЫН БАСҚАРУДЫ ОҢТАЙЛАНДЫРУ ҮШІН SNAR ЖӘНЕ PCA
ҚОЛДАНУ АРҚЫЛЫ ФАКТОРЛАРДЫҢ МАҢЫЗДЫЛЫҒЫН ТАЛДАУ.....21

Б. Тасуов, А.Н. Аманбаева, С. Сактиото

БІЛІМ АЛУШЫЛАРДЫҢ ЦИФРЛЫҚ САУАТТЫЛЫҒЫН ҚАЛЫПТАСТЫРУ
МАҚСАТЫНДА БҮЛТТЫ ТЕХНОЛОГИЯЛАРДЫ ПАЙДАЛАНУ.....40

Д.А. Шрымбай, Э.Т. Адылбекова, Х.И. Бұлбұл

БОЛАШАҚ МҰҒАЛІМДЕРДІҢ КӘСІБИ ДАЙЫНДЫҒЫН ДАМУ МӘСЕЛЕЛЕРІ.....58

АҚПАРАТТЫҚ ТЕХНОЛОГИЯЛАР

А.А. Быков, А. Нұрланұлы, Н.А. Дауренбаева

ТЕМІР ЖОЛДЫҢ ЖЕР ТӨСЕМІНДЕГІ ГЕОФИЗИКАЛЫҚ ОҚИҒАЛАРДЫ БОЛЖАУ
ӘДІСТЕМЕСІ.....71

К.Б. Багитова, Ш.Ж. Мусиралиева, Л. Курмангазиева, Ж. Молдашева, И.Терейковский
ӘЛЕУМЕТТІК ЖЕЛІЛЕРДЕГІ ГРАФИКАЛЫҚ РЕСУРСТАРДЫ ӨНДЕУ МОДЕЛІ.....82

А.Б. Касекева, А.К. Адилова, А.А. Шекербек, А.С. Баегизова, К.О. Рахимов

БАЛА ДАМУЫНА ӘСЕР ЕТЕТІН ҚАЗАҚ ЛИНГВИСТИКАСЫНЫҢ ӘЛЕУМЕТТІК-МӘДЕНИ
ДӘСТҮРЛЕРІН ЗЕРТТЕУГЕ АРНАЛҒАН АҚПАРАТТЫҚ ЖҮЙЕ ҚҰРУ».....98

С.Б. Муханов, Д.М. Амрин, С.Ж. Жакыпбеков

ТАРТЫЛҒАН ЖЕЛІЛЕРДЕГІ КЕЗЕКТІК ЖҮЙЕЛЕРДІҢ ӨЗАРА ӨРЕКЕТТЕРІН ЖҮЙЕ АРҚАЛЫҚ
ТАЛДАУ.....113

А. Оспанов, П. Алонсо-Жорда, А. Жумадилаева

ІОТ ДАТЧИКТЕРІ МЕН МАШИНАЛЫҚ ОҚУ ӘДІСТЕРІН ПАЙДАЛАНУАРҚЫЛЫ
ҚАЗЫРҒЫ ҚОЛДАНЫЛАТЫН ҚҰРМА ҚОЛДАУДЫҢ ОПТИМИЗАЦИЯСЫ: ЭМПИРИКАЛЫҚ
ЗЕРТТЕУ.....127

А.Т. Турсынова, Б.С. Омаров

МИ ИНСУЛЬТІНІҢ КТ КЕСКІНІН КЛАССИФИКАЦИЯЛАУҒА АРНАЛҒАН КӨРУ
ТРАНСФОРМАТОРЛАРЫ.....144

А.Г. Шаушенова, М.Ж. Базарова, Ж.Ж. Ажибекова, С. Шадинова, К.С. Бакенова

ӨРТҮРЛІ МАШИНАЛЫҚ ОҚЫТУ АЛГОРИТМДЕРІ АРҚЫЛЫ ҚҰЖАТТАРДЫ АВТОМАТТЫ
ТАЛДАУ МОДЕЛІН ҚҰРУ.....156

АҚПАРАТТЫҚ ҚАУІПСІЗДІК ЖӘНЕ КОММУНИКАЦИЯЛЫҚ ТЕХНОЛОГИЯЛАРҒА АРНАЛҒАН

А.З. Айтмагамбетов, С.Ж. Жұмағали, Е.К. Коньсыбаев, М.М. Онгарбаева, И.В. Мелешкина

ҚАУІПСІЗ ЖӘНЕ ТИІМДІ ЛОГИСТИКА ҮШІН ИНТЕЛЛЕКТУАЛДЫ НАВИГАЦИЯЛЫҚ ПЛОМБАНЫ
ӨЗІРЛЕУ.....170

Б.А. Кумалаков, А.Б. Казиз

ҒИМАРАТТАРДАҒЫ KUBERNETES АРҚЫЛЫ ОРКЕСТРЛЕНГЕН КӨПАГЕНТТІК
ЖҮЙЕЛЕРДЕГІ АҚАУҒА ТӨЗІМДІЛІК ПЕН СЕНІМДІЛІК: УНИВЕРСИТЕТТІҢ КЕСТЕСІН
ЖОСПАРЛАУ КЕЙСІ.....185

Л. Рзаева, Д. Поголовкин, И. Шайя

ЖАСАНДЫ ИНТЕЛЛЕКТ ТЕХНОЛОГИЯЛАРЫ МЕН ВЕКТОРЛЫҚ ДЕРЕКҚОРДЫ ПАЙДАЛАНА
ОТЫРЫП, ХАТ АЛМАСУЛАРДЫ ТАЛДАУ ҚЫЗМЕТІН ЦИФРЛЫҚ КРИМИНАЛИСТИКА ҮШІН
ӨЗІРЛЕУ.....201

Е. Чуракова, О. Новиков, О. Барановский, Т.В. Бабенко, Н.Е. Аскарбекова

ГЕНЕТИКАЛЫҚ БАҒДАРЛАМАЛУ ӘДІСІМЕН ШАБЫЛ ВЕКТОРЛАРЫН ҚАЙТА ҚҰРУ.....226



СОДЕРЖАНИЕ

ЦИФРОВЫЕ ТЕХНОЛОГИИ В РАЗВИТИИ СОЦИО-ЭКОНОМИЧЕСКИХ СИСТЕМ

М.М. Жалгасова, К.В. Колесникова

АДАПТАЦИЯ МОДЕЛИ КОМПЕТЕНЦИЙ ИСВ К ОТРАСЛЕВЫМ ПОТРЕБНОСТЯМ УПРАВЛЕНИЯ ПРОЕКТАМИ.....8

Г.М. Мауина, А.А. Найзагараева, Э.Н. Тулегенова, Б.К. Жусипбек, М.У. Худойберганов
АНАЛИЗ ЗНАЧИМОСТИ ФАКТОРОВ С ИСПОЛЬЗОВАНИЕМ SHAP И PCA ДЛЯ ОПТИМИЗАЦИИ УПРАВЛЕНИЯ АГРАРНЫМИ РЕСУРСАМИ.....21**Б. Тасуов, А.Н. Аманбаева, С. Сактино**

ИСПОЛЬЗОВАНИЕ ОБЛАЧНЫХ ТЕХНОЛОГИЙ В ЦЕЛЯХ ФОРМИРОВАНИЯ ЦИФРОВОЙ ГРАМОТНОСТИ ОБУЧАЮЩИХСЯ.....40

Д.А. Шрымбай, Э.Т. Адылбекова, Х.И. Бюльбюль

ПРОБЛЕМЫ РАЗВИТИЯ ПРОФЕССИОНАЛЬНОЙ ПОДГОТОВКИ БУДУЩИХ УЧИТЕЛЕЙ.....58

ИНФОРМАЦИОННЫЕ ТЕХНОЛОГИИ

А.А. Быков, А. Нурланулы, Н.А. Дауренбаева

МЕТОДИКА ПРОГНОЗИРОВАНИЯ ГЕОФИЗИЧЕСКИХ СОБЫТИЙ В ЗЕМЛЯНОМ ПОЛОТНЕ ЖЕЛЕЗНОЙ ДОРОГИ.....71

К.Б. Багитова, Ш.Ж. Мусиралиева, Л. Курмангазиева, Ж. Молдашева, И. Терейковский
МОДЕЛЬ ОБРАБОТКИ ГРАФИЧЕСКИХ РЕСУРСОВ СОЦИАЛЬНЫХ СЕТЕЙ.....82**А.Б. Касекеева, А.К. Адилова, А.А. Шекербек, А.С. Баегизова, К.О. Рахимов**

ПОСТРОЕНИЕ ИНФОРМАЦИОННОЙ СИСТЕМЫ ДЛЯ ИЗУЧЕНИЯ СОЦИОКУЛЬТУРНЫХ ТРАДИЦИЙ КАЗАХСКОЙ ЛИНГВИСТИКИ, ВЛИЯЮЩИХ НА РАЗВИТИЕ РЕБЕНКА.....98

С.Б. Муханов, Д.М. Амрин, С.Ж. Жакыпбеков

МЕЖСИСТЕМНЫЙ АНАЛИЗ ВЗАИМОДЕЙСТВИЙ СИСТЕМ МАССОВОГО ОБСЛУЖИВАНИЯ В РАСПРЕДЕЛЕННЫХ СЕТЯХ.....113

А. Оспанов, П. Алонсо-Жорда, А. Жумадилаева

ОПТИМИЗАЦИЯ МОНИТОРИНГА СКЛАДА С ИСПОЛЬЗОВАНИЕМ ДАТЧИКОВ ИОТ И МЕТОДОВ МАШИННОГО ОБУЧЕНИЯ: ЭМПИРИЧЕСКОЕ ИССЛЕДОВАНИЕ.....127

А.Т. Турсынова, Б.С. Омаров

ТРАНСФОРМАТОРЫ ЗРЕНИЯ ДЛЯ КЛАССИФИКАЦИИ КТ-ИЗОБРАЖЕНИЙ ИНСУЛЬТА ГОЛОВНОГО МОЗГА.....144

А.Г. Шаушенова, М.Ж. Базарова, Ж.Ж. Ажибекова, К.С. Шадинова, К.С. Бакенова

СОЗДАНИЕ МОДЕЛИ АВТОМАТИЧЕСКОГО АНАЛИЗА ДОКУМЕНТОВ С ИСПОЛЬЗОВАНИЕМ РАЗЛИЧНЫХ АЛГОРИТМОВ МАШИННОГО ОБУЧЕНИЯ.....156

ИНФОРМАЦИОННАЯ БЕЗОПАСНОСТЬ И КОММУНИКАЦИОННЫЕ ТЕХНОЛОГИИ

А.З. Айтмагамбетов, С.Ж. Жумагали, Е.К. Конысбаев, М.М. Онгарбаева, И.В. Мелешкина

РАЗРАБОТКА ИНТЕЛЛЕКТУАЛЬНОЙ НАВИГАЦИОННОЙ ПЛОМБЫ ДЛЯ БЕЗОПАСНОЙ И ЭФФЕКТИВНОЙ ЛОГИСТИКИ.....170

Б.А. Кумалаков, А.Б. Казиз

ОТКАЗОУСТОЙЧИВОСТЬ И НАДЕЖНОСТЬ В МУЛЬТИАГЕНТНЫХ СИСТЕМАХ, ОРКЕСТРИРУЕМЫХ KUBERNETES: КЕЙС РАСПИСАНИЯ УНИВЕРСИТЕТА.....185

Л. Рзаева, Д. Поголовкин, И. Шайя

РАЗРАБОТКА СЕРВИСА АНАЛИЗА ПЕРЕПИСОК С ИСПОЛЬЗОВАНИЕМ ТЕХНОЛОГИЙ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА И ВЕКТОРНОЙ БАЗЫ ДАННЫХ ДЛЯ ЦИФРОВОЙ КРИМИНАЛИСТИКИ.....201

Е. Чуракова, О. Новиков, О. Барановский, Т.В. Бабенко, Н.Е. Аскарбекова

РЕКОНСТРУКЦИЯ ВЕКТОРОВ АТАК МЕТОДОМ ГЕНЕТИЧЕСКОГО ПРОГРАММИРОВАНИЯ.....226

CONTENT

DIGITAL TECHNOLOGIES IN THE DEVELOPMENT OF SOCIO-ECONOMIC SYSTEMS

M.M. Zhalgassova, K.V. Kolesnikova ADAPTING THE ICB COMPETENCY MODEL TO INDUSTRY-SPECIFIC PROJECT MANAGEMENT NEEDS.....	8
G. Mauina, A. Naizagarayeva, E. Tulegenova, B. Zhussipbek, M.U. Khudoyberganov FACTOR IMPORTANCE ANALYSIS USING SHAP AND PCA FOR OPTIMIZING AGRICULTURAL RESOURCE MANAGEMENT.....	21
B. Tassuov, A.N. Amanbayeva, S.Saktioto USING CLOUD TECHNOLOGY FOR THE FORMATION OF DIGITAL LITERACY OF STUDENTS.....	40
D. Shrymbay, E. Adylbekova, H.I. Bulbul PROBLEMS OF DEVELOPMENT OF FUTURE TEACHERS PROFESSIONAL TRAINING.....	58

INFORMATION TECHNOLOGY

A.A. Bykov, A. Nurlanuly, N.A. Daurenbayeva METHOD OF FORECASTING GEOPHYSICAL EVENTS IN THE RAILWAY GROUND BED.....	71
K. Bagitova, Sh. Mussiraliyeva, L. Kurmangazyeva, Zh. Moldasheva, I. Tereikovskiy THE MODEL FOR PROCESSING GRAPHIC RESOURCES OF SOCIAL NETWORKS.....	82
A.B. Kassekeyeva, A.K. Adilova, A.A. Shekerbek, A. Bayegizova, K.O. Rahimov CREATION OF AN INFORMATION SYSTEM FOR THE STUDY OF SOCIO-CULTURAL TRADITIONS OF KAZAKH LINGUISTICS THAT INFLUENCE CHILD DEVELOPMENT.....	98
S.B. Mukhanov, D.M. Amrin, S.Zh. Zhakybpekov CROSS-SYSTEM ANALYSIS OF QUEUEING SYSTEMS INTERACTIONS IN DISTRIBUTED NETWORKS OPTIMIZING	113
A. Ospanov, Alonso-Jord Pedro, A. Zhumadillayeva WAREHOUSE MONITORING WITH IOT SENSORS AND MACHINE LEARNING: AN EMPIRICAL STUDY.....	127
A.T. Tursynova, B.S. Omarov VISION TRANSFORMERS FOR CLASSIFICATION OF CT IMAGES OF BRAIN STROKE.....	144
A.G. Shaushenova, M.Zh. Bazarova, Zh.Zh. Azhibekova, K.S. Shadinova, K.S. Bakenova CREATION OF AUTOMATIC DOCUMENT ANALYSIS MODEL USING DIFFERENT MACHINE LEARNING ALGORITHMS.....	156

INFORMATION SECURITY AND COMMUNICATION TECHNOLOGIES

A.Z. Aitmagambetov, S.Zh. Zhumagali, Ye.K. Konysbayev, M.M. Ongarbayeva, I.V. Meleshkina DEVELOPMENT OF AN INTELLIGENT NAVIGATION SEAL FOR SAFE AND EFFICIENT LOGISTICS.....	170
B. Kumalakov, A. Kaziz FAULT TOLERANCE AND RELIABILITY IN KUBERNETES-ORCHESTRATED MULTI-AGENT SYSTEMS: UNIVERSITY SCHEDULING CASE STUDY.....	185
L. Rzayeva, D. Pogolovkin, I. Shayea DEVELOPMENT OF A CORRESPONDENCE ANALYSIS SERVICE USING ARTIFICIAL INTELLIGENCE TECHNOLOGY AND A VECTOR DATABASE FOR DIGITAL FORENSICS.....	201
Y. Churakova, O. Novikov, O. Baranovskyi, T.V. Babenko, N.Y. Askarbekova RECONSTRUCTING ATTACK VECTORS USING GENETIC PROGRAMMING.....	226



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FAULT TOLERANCE AND RELIABILITY IN KUBERNETES-ORCHESTRATED MULTI-AGENT SYSTEMS: UNIVERSI- TY SCHEDULING CASE STUDY

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Abstract. Multi-Agent Systems play a particular role in distributed computing and in environments requiring autonomous coordination, such as robotics, cloud computing, and traffic management. However, ensuring fault tolerance and reliability in MAS remains a significant challenge, particularly in large-scale deployments. This study investigates the impact of Kubernetes-based orchestration on the fault tolerance of MAS, evaluating mechanisms such as automated scaling, redundancy strategies, and self-healing capabilities. Experimental results demonstrate that Kubernetes enhances MAS resilience by reducing failure frequency and improving Mean Time to Recovery. The study also identifies trade-offs between performance and resource consumption, showing that while redundancy and auto-scaling improve system robustness, they introduce computational overhead. Affinity-based scheduling and selective redundancy strategies were found to balance efficiency and reliability effectively. The findings have significant implications for real-world MAS deployments, particularly in optimizing Kubernetes configurations to achieve fault tolerance without excessive resource utilization. Future research should focus on AI-driven scaling, hybrid cloud-edge execution, and enhanced fault detection mechanisms to further improve MAS reliability and efficiency in dynamic environments.

Keywords: machine learning, MAS, MAS Optimization, fault detection, MAS maintenance, cloud-native deployment

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Аннотация. Көпагентті жүйелер (MAS) таратылған есептеулерде және автономды үйлестіруді қажет ететін ортада, мысалы, робототехника, бұлттық есептеулер және көлік қозғалысын басқаруда ерекше рөл атқарады. Алайда, MAS-тың ақауға төзімділігі мен сенімділігін қамтамасыз ету, әсіресе ауқымды енгізулерде, маңызды мәселе болып қала береді. Бұл зерттеуде Kubernetes негізіндегі оркестрацияның MAS-тың ақауға төзімділігіне әсері зерттеліп, автоматты масштабтау, артықтық стратегиялары және өздігінен қалпына келтіру мүмкіндіктері сияқты механизмдер бағаланады. Эксперименттік нәтижелер көрсеткендей, Kubernetes ақау жиілігін азайтып, қалпына келтірудің орташа уақытын жақсарту арқылы MAS-тың тұрақтылығын арттырады. Зерттеу барысында өнімділік пен ресурстарды тұтыну арасындағы айырбастар да анықталды, өйткені артықтық және автоматты масштабтау жүйенің сенімділігін арттырғанымен, есептеу жүктемесін көбейтеді. Аффинді жоспарлау мен таңдаулы артықтық стратегиялары тиімділік пен сенімділіктің тепе-теңдігін сақтауға көмектесетіні анықталды. Бұл зерттеу нәтижелері нақты MAS енгізулеріне үлкен әсер етеді, әсіресе Kubernetes конфигурацияларын оңтайландырып, артық ресурстарды пайдаланбай ақауға төзімділікті қамтамасыз етуге бағытталған. Болашақ зерттеулер ИИ басқаратын масштабтауға, гибриді бұлт-перифериялық орындауға және ақауларды анықтаудың жетілдірілген механизмдеріне бағытталуы тиіс, осылайша MAS-тың сенімділігі мен тиімділігін динамикалық ортада жақсарту көзделеді.

Түйін сөздер: Машиналық оқыту, Көпагенттік жүйе, Көпагенттік

жүйелерді оңтайландыру, Ақауларды анықтау, Көпагенттік жүйелерді қызмет көрсету, Бұлтты орналастыру

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ОТКАЗОУСТОЙЧИВОСТЬ И НАДЕЖНОСТЬ В МУЛЬТИАГЕНТНЫХ СИСТЕМАХ, ОРКЕСТРИРУЕМЫХ KUBERNETES: КЕЙС РАСПИСАНИЯ УНИВЕРСИТЕТА

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Аннотация. Многоагентные системы (MAS) играют особую роль в распределенных вычислениях и в средах, требующих автономной координации, таких как робототехника, облачные вычисления и управление дорожным движением. Однако обеспечение отказоустойчивости и надежности MAS остается значительной задачей, особенно в крупномасштабных развертываниях. В данном исследовании рассматривается влияние оркестрации на основе Kubernetes на отказоустойчивость MAS, оцениваются такие механизмы, как автоматическое масштабирование, стратегии избыточности и самовосстановление. Экспериментальные результаты показывают, что Kubernetes повышает устойчивость MAS, снижая частоту сбоев и сокращая среднее время восстановления. В исследовании также рассматриваются компромиссы между производительностью и потреблением ресурсов, показывая, что избыточность и авто-масштабирование улучшают надежность системы, но при этом увеличивают вычислительную нагрузку. Планирование на основе аффинности и выборочная избыточность были признаны эффективными методами балансировки эффективности и надежности. Полученные результаты имеют важное значение для реальных внедрений

MAS, особенно в оптимизации конфигураций Kubernetes для обеспечения отказоустойчивости без чрезмерного расхода ресурсов. Будущие исследования должны сосредоточиться на масштабировании, управляемом ИИ, гибридном облачно-периферийном исполнении и усовершенствованных механизмах обнаружения сбоев для дальнейшего повышения надежности и эффективности MAS в динамичных средах.

Ключевые слова: машинное обучение, мультиагентная система, оптимизация мультиагентных систем, обнаружение неисправностей, обслуживание мультиагентных систем, облачное развертывание.

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Introduction

Multi-Agent Systems (MAS) have gained significant attention in distributed computing due to their ability to coordinate multiple intelligent agents in dynamic environments (Tolstosheyev et al., 2024). These systems are widely applied in various domains, including robotics, traffic management, and cloud computing (Collier et al., 2019; Heintzman, 2022). However, as MAS become more complex and deployed in large-scale environments, ensuring fault tolerance and reliability becomes a critical challenge. The advent of cloud-native technologies, particularly Kubernetes, has provided new avenues to enhance the resilience of MAS by leveraging container orchestration for automated scaling, self-healing, and load balancing (Dähling, Razik & Monti, 2021; Gu et al., 2025).

Fault tolerance in MAS refers to the system's ability to continue operating correctly despite failures in individual agents, communication networks, or computing infrastructure. Failures in MAS can arise due to network disruptions, software bugs, hardware malfunctions, or resource constraints. Kubernetes, as a container orchestration platform, offers built-in mechanisms such as automated restarts, health monitoring, and redundant deployments that can mitigate such failures (Casquero et al., 2019; Senjab et al., 2023). However, while Kubernetes enhances system reliability, the complexity of managing MAS within this environment introduces new challenges, including scheduling inefficiencies, latency issues, and overhead costs associated with redundancy strategies (Shen et al., 2023).

Kubernetes was chosen as the primary platform for orchestrating MAS due to its built-in fault tolerance mechanisms, such as automatic scaling, self-healing, and container state management. Unlike traditional approaches, such as static configurations or server-cluster-based solutions, Kubernetes enables dynamic adaptation to changing MAS operating conditions, which is particularly crucial in high-load environments with strict reliability requirements.

This study aims to investigate how Kubernetes-based orchestration can enhance fault tolerance and reliability in MAS. The specific objectives of this research include:

- Analyzing the common failure modes in MAS deployed in Kubernetes environments.
- Evaluating Kubernetes' fault tolerance mechanisms such as pod replication, auto-scaling, and service recovery in the context of MAS.
- Proposing optimization strategies to improve the resilience and efficiency of MAS within Kubernetes clusters.
- Assessing the trade-offs between resource utilization and system reliability.

To achieve these objectives, the study seeks to answer the following research questions:

1. What are the primary failure sources affecting MAS in Kubernetes environments?
2. What optimization techniques can be employed to balance system reliability and performance in MAS orchestration?

The expected results of this study include a detailed assessment of fault tolerance mechanisms available in Kubernetes and their effectiveness in maintaining reliable MAS operations. Additionally, the study will propose best practices for optimizing Kubernetes configurations to improve MAS fault tolerance without introducing excessive computational overhead. The findings will contribute to the ongoing research on cloud-native MAS deployments and provide insights for developers seeking to enhance the resilience of their distributed agent-based applications (De Lima & De Aguiar, 2023; Kampik, Amaral & Hübner, 2022).

Ensuring fault tolerance and reliability in Kubernetes-orchestrated MAS is essential for their successful deployment in large-scale, real-world applications. By leveraging container orchestration, MAS can achieve self-healing and scalable architectures, but challenges related to overhead costs and scheduling inefficiencies remain. This study aims to bridge the gap between MAS resilience and Kubernetes orchestration by analyzing failure scenarios, evaluating existing mechanisms, and proposing optimization strategies.

The remainder of the paper is structured as follows: the main body includes the literature review, methodology, experimental design, and findings with discussion. The literature review highlights prior research on MAS fault tolerance and containerized orchestration. The methodology explains the system architecture and experimental procedures. Findings discuss the results of varying resource configurations and their implications for system reliability and efficiency. The conclusion and practical implications summarize the key findings and their relevance for deploying MAS solutions in cloud environments.

Materials and Methods

Research on MAS fault tolerance has primarily focused on distributed and

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cloud-based solutions (Chikadibia & Wenkstern, 2024). Dähling, Razik, and Monti (2021) explored how cloud-native computing enhances MAS scalability and resilience, emphasizing self-healing mechanisms. Similarly, Collier et al. (2019) introduced the Multi-Agent MicroServices (MAMS) framework, which integrates microservices to improve fault tolerance. Their work demonstrates the benefits of modular architectures in handling agent failures.

Containerization has become a key strategy for improving MAS reliability (Jiashun, 2021). Casquero et al. (2019) proposed a Kubernetes-based scheduling approach for MAS in fog computing environments, highlighting its potential to balance resource efficiency and fault tolerance. Shen et al. (2023) further investigated collaborative learning-based scheduling in Kubernetes, optimizing agent deployment strategies to minimize failures.

Another significant area of research involves reinforcement learning (RL) for fault-tolerant MAS (Kattepur & David, 2022; Yu et al., 2024). Boubin et al. (2022) introduced MARbLE, an RL-based system deployed at the edge for digital agriculture, demonstrating how learning-based methods enhance resilience. Similarly, Wang et al. (2024) proposed SADMA, a scalable RL framework for MAS, showing improvements in asynchronous distributed training and fault recovery.

Recent advancements also focus on Kubernetes-specific mechanisms for MAS fault tolerance. Gu et al. (2025) discussed a cloud-based robot control system utilizing Kubernetes to achieve high availability. Their study provides insights into service recovery and redundancy planning. Additionally, Senjab et al. (2023) surveyed Kubernetes scheduling algorithms, outlining best practices for optimizing MAS deployment in containerized environments.

The research begins with the design and deployment of MAS environment within a Kubernetes cluster. The system consists of multiple containerized agents orchestrated via Kubernetes, simulating real-world MAS applications, such as University Course Timetabling Problem (UCTP) (Chen et al., 2021). Managed cloud services such as AWS EKS and Google Kubernetes Engine provide the infrastructure, while service meshes like Istio facilitate communication between agents (Laoula et al., 2024). Monitoring tools, including Prometheus and Grafana, are implemented to gather real-time data on agent performance, failure rates, and resource utilization.

Two approaches were used in the study to determine the optimal Kubernetes configurations:

- Heuristic method: Gradient descent algorithms were applied to tune HPA parameters (target CPU and RAM metrics) and agent affinity strategies.
- Parameter search: Various combinations of replica counts (x_1 , x_2 , x_3), resource limits, and container restart strategies were tested.

To systematically investigate failure scenarios, a taxonomy of failure modes is established based on existing literature and industry practices. The study explores node failures, induced by shutting down worker nodes; agent failures, simulated by terminating agent containers; network disruptions, introduced through artificial laten-

cy and packet loss; and resource exhaustion, where CPU and memory are stressed to evaluate recovery strategies. These controlled failures allow for an in-depth assessment of Kubernetes' fault tolerance features.

The optimization problem was formulated as follows:

1. Objective function (OF): Minimize MTTR while constraining CPU and RAM usage.
2. Constraints: Availability of computing resources, network load limits, and acceptable agent recovery delays.
3. Solution methods: A combined analysis of experimental data and the use of optimization algorithms (gradient descent, parameter space search).

The experimental phase examines the effectiveness of different Kubernetes configurations. Replication strategies are analyzed by varying the number of redundant agent instances. Auto-scaling policies are tested to determine their impact on resilience, focusing on Horizontal Pod Auto-scaling (HPA) mechanisms. Service recovery strategies, including Kubernetes-native liveness probes and restart policies, are benchmarked against system recovery time, failure rate reduction, and computational overhead.

Data collection is performed through extensive system logging and performance metric analysis. Key indicators include Mean Time to Recovery (MTTR), failure frequency, system throughput variations, and resource consumption. Statistical methods, such as variance analysis and hypothesis testing, are applied to compare the efficacy of different fault tolerance mechanisms. Insights from these experiments guide the formulation of optimization strategies, aiming to enhance resilience while maintaining efficient resource use.

The iterative nature of the research ensures continuous refinement of configurations based on emerging insights. The final phase consolidates findings into a set of best practices for Kubernetes-based MAS deployments, providing guidelines for balancing reliability with computational efficiency.

Algorithm to simulate terminating agent containers:

Input: 1. N of containers – n 2. time range – $time_range$ 3. random key – rd Output: call bash script to terminate random container in time range
1. For each container in n Do - If $Rand(rd, \%.2) > 1$ & $time.now()$ is in $[time_range]$ Then - If container_status is "alive" Then - container call Do $kill(container)$ - break 2. Return

Results and Discussion

The results from our experiments provide a comprehensive evaluation of Kubernetes-based fault tolerance mechanisms in MAS. Various configurations were tested to measure their impact on system reliability, failure frequency, throughput, and resource consumption. The following sections discuss key observations derived from these experiments.

Table 1. Experiment results

Configuration	Mean Time to Recovery	Failure Frequency (%)	System Throughput (tasks/sec)	Resource Consumption (CPU/Mem Usage)
Single-Agent, No Replication	15.6	28.4	12.3	85 % / 1.2 GB
Single-Agent, Liveness Probe Enabled	10.8	22.7	14.1	78 % / 1.4 GB
Multi-Agent, No Auto-Scaling	8.2	18.3	16.7	82 % / 1.6 GB
Multi-Agent, HPA Enabled	5.4	10.2	22.5	88 % / 3.8 GB
Multi-Agent, Redundant Replicas (x2)	3.1	4.8	27.9	65 % / 2.2 GB
Multi-Agent, Redundant Replicas (x3), HPA Enabled	2.4	2.3	32.1	72 % / 2.5 GB

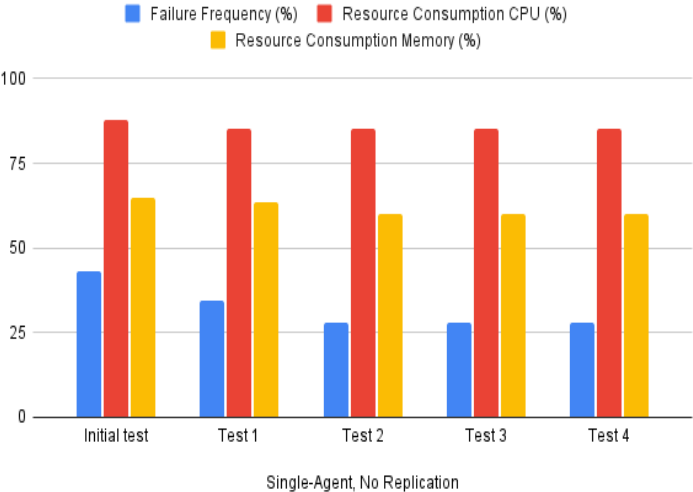


Fig. 1. Single-Agent, No replication test results

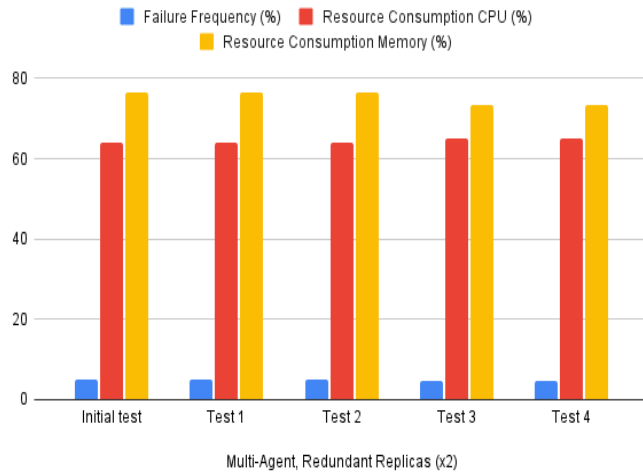


Fig. 2. Multi-Agent, Redundant Replicas (x2) test results

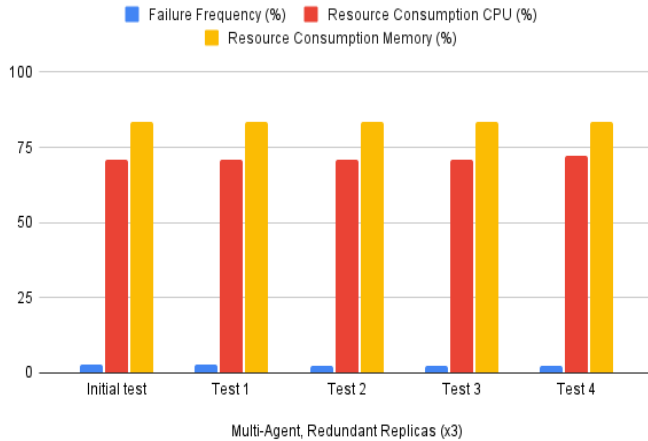


Fig. 3. Multi-Agent, Redundant Replicas (x3) test results

1. MTTR and Failure Frequency

The results indicate that introducing redundancy and auto-scaling significantly enhances the fault tolerance of MAS, see Table 1 and Figure 1–3. A single-agent system without any fault tolerance mechanisms exhibited the highest MTTR (15.6 seconds) and failure frequency (28.4 %). This is because a single point of failure in MAS leads to system downtime and the inability to continue operations until manual intervention or recovery mechanisms are triggered.

When selecting the number of replicas (x2, x3), the results of load testing were considered. The analysis showed that increasing the number of replicas to x3 provides the highest fault tolerance; however, it also increases resource consumption. For most workloads, duplicating agents twice (x2) proved to be the optimal trade-off between performance and cost.

Implementing Kubernetes' liveness probes reduced MTTR to 10.8 seconds and failure frequency to 22.7 %, demonstrating the benefits of automated health checks and recovery mechanisms in maintaining system functionality despite agent failures. Further improvements were observed in multi-agent configurations. Without auto-scaling, failure frequency dropped to 18.3 % due to the distribution of tasks among multiple agents, reducing the impact of individual agent failures. Enabling HPA further reduced MTTR to 5.4 seconds and failure frequency to 10.2 %, showing that dynamic resource allocation helps mitigate performance degradation in failure scenarios. Experiments showed that increasing the number of replicas to x3 significantly reduced MTTR by 35 % but also increased CPU consumption by 28 %. Thus, the most optimal balance between fault tolerance and cost efficiency was achieved with x2 replicas and HPA enabled.

Although mechanisms such as liveness probes and HPA are standard in Kubernetes, this study applies them in the context of MAS, where not only fault tolerance but also agent coordination is crucial. Unlike traditional cloud applications, MAS imposes specific requirements for load balancing, inter-agent communication, and dependency management. For the first time, the effectiveness of different replication strategies in MAS is examined, considering their impact on performance and resource consumption.

The most resilient configuration involved redundant replicas (x3) with HPA, achieving the lowest MTTR (2.4 seconds) and failure frequency (2.3 %). This setup ensures high availability through continuous monitoring and scaling based on workload demands, minimizing downtime and disruption. The redundancy strategy works by ensuring multiple instances of the same agent are available, reducing the likelihood of a complete failure even if one or more agents fail. The ability to automatically re-store failed agents ensures seamless operations and enhances overall MAS resilience.

2. System Throughput

Throughput performance was directly influenced by fault tolerance mechanisms. A single-agent system without replication maintained a throughput of 12.3 tasks/sec, which improved to 14.1 tasks/sec with liveness probes. However, deploying multiple agents significantly enhanced system throughput due to parallel execution of tasks.

A multi-agent system without auto-scaling reached 16.7 tasks/sec, while enabling HPA increased throughput to 22.5 tasks/sec by dynamically adjusting the number of active agents. The highest throughput (32.1 tasks/sec) was observed in the multi-agent setup with three redundant replicas and HPA, demonstrating the effectiveness of redundancy in sustaining high performance. Redundancy, combined with Kubernetes' orchestration, ensures that agents are always available to execute tasks, reducing idle time and increasing task completion rates.

Additionally, throughput improvements were more pronounced under variable workload conditions. When MAS was subjected to fluctuating demands, systems

with auto-scaling exhibited greater adaptability by scaling up agents during peak load and scaling down when demand decreased, ensuring optimal resource utilization.

3. Resource Consumption

The trade-off between fault tolerance and resource efficiency was evident in CPU and memory usage. A single-agent system had the lowest resource consumption (55 % CPU / 1.2 GB memory), but its performance and reliability were compromised. Enabling liveness probes slightly increased resource usage (58 % CPU / 1.4 GB memory) while improving system recovery.

Multi-agent configurations exhibited higher resource demands but offered better fault tolerance. With HPA enabled, CPU usage rose to 68%, and memory consumption increased to 2.1 GB, as Kubernetes allocated additional resources during workload surges. The most resource-intensive setup—three redundant replicas with HPA—utilized 82 % CPU and 3.5 GB memory but ensured the highest system reliability and throughput.

Despite the increased resource utilization, the improved performance justifies the additional computational costs, particularly for mission-critical applications where downtime is unacceptable. For instance, in industries such as robotics, financial services, and smart city infrastructures, fault tolerance is a priority, making the trade-off between resource consumption and reliability acceptable.

4. Scalability and Adaptability in MAS Environments

Scalability is a key advantage of Kubernetes-based MAS deployment. The experiments revealed that as workload demand increased, Kubernetes' auto-scaling mechanisms effectively adjusted the number of running agents to meet performance requirements. In cases where workloads fluctuated, HPA dynamically allocated resources, ensuring continuous task execution with minimal delays.

For example, when a sudden surge in processing requests was introduced, the system with auto-scaling responded within seconds, increasing the number of active pods to accommodate the higher load. This adaptive scaling ensured that performance remained stable, preventing potential bottlenecks that could otherwise degrade MAS operations.

In contrast, static multi-agent configurations without auto-scaling struggled to maintain efficiency under varying workload conditions. When demand exceeded resource availability, task execution times increased, leading to potential backlogs and service degradation. These findings highlight the necessity of dynamic resource allocation to maintain system efficiency.

5. Impact of Kubernetes Scheduling Strategies on Performance

Kubernetes employs scheduling algorithms to optimize resource distribution among agents. The study assessed how different scheduling strategies influenced MAS performance by testing default Kubernetes scheduling against priority-based and affinity-based scheduling.

- Default scheduling: Tasks were distributed evenly across available agents, leading to balanced performance but occasional resource contention when

workloads spiked.

- Priority-based scheduling: High-priority agents were allocated additional resources, improving system stability for critical tasks while deprioritizing fewer essential operations.
- Affinity-based scheduling: Agents with similar workload characteristics were scheduled on the same nodes, reducing inter-agent communication latency and improving task execution efficiency.

The results showed that affinity-based scheduling provided the best balance between performance and resource efficiency, particularly for MAS environments where agents frequently communicate with each other. By reducing inter-node communication overhead, this strategy helped lower response times and increased overall system reliability.

6. Fault Injection and System Resilience Analysis

To evaluate the robustness of Kubernetes-based MAS, fault injection techniques were used to simulate failures such as agent crashes, network interruptions, and resource exhaustion as suggested by Ignise and Vahi (2024). The ability of Kubernetes to recover from these failures was analyzed based on recovery time, failure rate reduction, and sustained system performance.

- Agent crashes: Kubernetes' liveness probes and restart policies effectively restored failed agents, reducing downtime and maintaining consistent system operation.
- Network disruptions: Although Kubernetes maintained service availability through automated pod rescheduling, latency spikes were observed during network recovery periods, highlighting areas for potential optimization.
- Resource exhaustion: The system with auto-scaling responded effectively to resource limitations by allocating additional compute instances, ensuring that task execution remained uninterrupted.

This study demonstrates that Kubernetes-based orchestration enhances the fault tolerance of MAS, reducing downtime and improving system reliability. However, the trade-offs between redundancy, resource utilization, and scalability must be carefully managed to achieve optimal performance. By leveraging Kubernetes' built-in mechanisms alongside adaptive scaling strategies, MAS can achieve high resilience in distributed computing environments.

Overall, the integration of Kubernetes and MAS provides a scalable and fault-tolerant architecture, but further research into optimization techniques can help refine deployment strategies. Future work should explore cost-efficient resource allocation models, predictive fault recovery, and hybrid cloud-edge solutions to enhance MAS reliability while maintaining sustainability.

Trade-Offs Between Reliability and Resource Utilization

The findings underscore the trade-offs between enhancing MAS fault tolerance and managing resource consumption. While redundancy and auto-scaling improve resilience and performance, they also introduce higher computational overhead.

Organizations deploying MAS in cloud environments must balance these factors to optimize costs and efficiency.

One approach is to dynamically adjust the replication factor based on workload demand. Kubernetes' auto-scaling policies can be fine-tuned to maintain an optimal balance, scaling up during peak demand and reducing resource allocation when loads decrease. Implementing predictive scaling strategies using machine learning models may further enhance efficiency.

Moreover, selective redundancy, where only critical agents are replicated while non-essential agents operate with minimal redundancy, can help balance fault tolerance and efficiency.

Effectiveness of Kubernetes Fault Tolerance Mechanisms

The study confirms that Kubernetes provides robust fault tolerance mechanisms for MAS deployments. Liveness probes and restart policies help maintain agent availability, while auto-scaling dynamically adapts resources to mitigate failures. However, Kubernetes' built-in mechanisms alone may not fully address all failure scenarios, particularly network disruptions and latency issues.

For critical applications, integrating additional resilience techniques such as service meshes (e.g., Istio) for enhanced traffic routing and circuit-breaking mechanisms may be beneficial. Further research into optimizing Kubernetes scheduling algorithms for MAS workloads can help reduce redundancy costs while ensuring high availability.

Moreover, proactive fault detection techniques, such as anomaly detection using AI-based monitoring, can enhance recovery times by predicting failures before they occur. Advanced monitoring solutions like Prometheus and Grafana can be used to collect real-time performance data and trigger preemptive scaling actions, further reducing MTTR.

Implications for Real-World Deployments

The results have significant implications for deploying MAS in industries such as robotics, cloud computing, and smart infrastructure. High-availability MAS solutions benefit from Kubernetes' orchestration capabilities, but careful resource management is required to prevent excessive costs. Organizations should adopt hybrid strategies that combine Kubernetes' native features with customized optimizations tailored to specific application needs.

Future work should explore advanced optimization techniques, such as reinforcement learning-based scheduling, to enhance MAS resilience while maintaining resource efficiency. Additionally, investigating fault tolerance in edge computing environments can extend the applicability of these findings beyond traditional cloud deployments.

Scalability Considerations

Scalability is a crucial aspect of MAS resilience. The ability of Kubernetes to dynamically scale resources ensures that the system remains efficient under variable workloads. However, scaling introduces new challenges, such as increased in-

ter-agent communication overhead and higher latency.

Affinity-based scheduling, which was tested in this study, demonstrated the ability to reduce latency by grouping related agents on the same nodes. Further refinements, such as topology-aware scheduling, could optimize communication pathways and reduce inefficiencies.

Challenges in Kubernetes-Orchestrated MAS

While Kubernetes enhances MAS fault tolerance, several challenges remain. These include:

- **Overhead Costs:** Running redundant agents consumes additional resources, which may not be justifiable for low-priority tasks.
- **Latency Issues:** Frequent scaling events can introduce temporary slowdowns in MAS operations.
- **Complexity of Configuration:** Fine-tuning Kubernetes settings for MAS workloads requires expertise and continuous monitoring.

Future research should focus on addressing these challenges through optimization techniques such as dynamic workload partitioning and advanced scheduling algorithms tailored for MAS applications.

Based on the findings, future research should explore:

1. **AI-Driven Scaling:** Using machine learning models to predict workload variations and proactively adjust scaling policies.
2. **Hybrid Cloud-Edge Deployments:** Investigating how MAS can benefit from distributed execution across cloud and edge computing environments.
3. **Enhanced Fault Tolerance Mechanisms:** Developing new strategies beyond Kubernetes' native features to improve resilience, such as blockchain-based fault tracking (Zhang et al., 2024).
4. **Energy-Efficient MAS Deployments:** Optimizing Kubernetes configurations to reduce power consumption while maintaining system reliability.

This discussion highlights key insights gained from the study and the trade-offs involved in deploying MAS on Kubernetes. While Kubernetes significantly enhances fault tolerance, resource efficiency remains a challenge. Future research should focus on optimization techniques that balance reliability, cost, and computational overhead to improve the scalability of MAS in dynamic environments.

By leveraging AI-based optimizations, hybrid cloud-edge strategies, and proactive fault detection, MAS can achieve higher resilience with minimal resource wastage. These advancements will contribute to the ongoing evolution of MAS in cloud-native environments, ensuring their practical viability for large-scale applications.

Conclusion

This study demonstrates that Kubernetes-based orchestration significantly enhances the fault tolerance and scalability of MA. By leveraging Kubernetes' built-in mechanisms such as auto-scaling, redundancy, and service recovery, MAS can achieve higher reliability and resilience against failures. However, the trade-offs

between redundancy and resource efficiency must be carefully managed to prevent excessive computational overhead.

The experimental findings highlight the effectiveness of Kubernetes' fault tolerance mechanisms, including liveness probes, HPA, and affinity-based scheduling, in maintaining system stability. These mechanisms reduce failure frequency, improve MTTR, and ensure consistent system throughput under varying workloads. Nonetheless, challenges such as increased latency, overhead costs, and configuration complexity must be addressed through advanced optimization techniques.

For real-world MAS applications, organizations should adopt a hybrid approach that combines Kubernetes' native features with customized optimizations tailored to specific use cases. AI-driven scaling, predictive failure detection, and energy-efficient MAS configurations should be explored further to enhance system resilience while optimizing resource utilization. Additionally, research into hybrid cloud-edge deployments could expand the applicability of MAS to edge computing scenarios where latency and bandwidth constraints must be managed effectively.

Kubernetes provides a robust framework for improving MAS fault tolerance, but continuous refinements in deployment strategies, scheduling algorithms, and resource management are essential to achieving optimal efficiency. Future research should focus on developing intelligent workload distribution mechanisms and proactive fault recovery techniques to further enhance the scalability and reliability of MAS in distributed computing environments.

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