ISSN 2782-6333

125

SUSTAINABLE DEVELOPMENT and ENGINEERING ECONOMICS

03 2024

Published by Peter the Great St. Petersburg Polytechnic University

Publisher
Peter the Great St. Petersburg
Polytechnic University
Corresponding address:
29 Polytechnicheskaya st., Saint-Petersburg,
195251, Russia
Contacts:
Email: sustainable@spbstu.ru
Web: https://sustainable.spbstu.ru/

Учредитель
Санкт-Петербургский политехнический университет Петра Великого
Адрес:
195251, Россия, Санкт-Петербург, Политехническая 29
Контакты:
Почта: sustainable@spbstu.ru
Веб-сайт: https://sustainable.spbstu.ru/

Technological Innovations and Human Capital Development for Economic Sustainability

In the contemporary landscape of global economies, competitiveness plays a crucial role in national and regional development. It requires a skilled workforce, accurate economic forecasting and robust data security solutions such as automated drones that utilize advanced encryption technologies. Understanding these interrelated aspects is vital for building economic resilience and achieving sustainable growth.

In the third issue of Sustainable Development and Engineering Economics for 2024, journal contributors examine various aspects of sustainable economic development and management models in different sectors.

The first section, ‘Economics of Engineering and Innovation Decisions as a Part of Sustainable Development’, features the article ‘Agile Project Management System with Intellectual Module for Prediction of Project Duration’ by Denisov, Gintciak, Burlutskaya, Fedyaevskaya and Beketov. The authors present a project management system designed to address the challenges of updating requirements to manage backlogs and tasks, incorporating a module to predict task durations. The module uses expert story points to evaluate tasks and Monte Carlo simulations to predict dynamic task durations. Integrating the developed method into a project management system reduced the assumptions and limitations associated with updating user story data, and involving new and cross-functional teams in projects.

The section ‘Enterprises and Sustainable Development of Regions’ presents the article ‘Improving the Information Security of Industrial Enterprises Through the Automation of Data and Information Message Transmission Processes’ by Buchaev and Polyakov. The authors examine the automation of data transmission security in industrial enterprises via an autonomous drone equipped with microcontrollers for flight control and data protection. Utilizing infrared channels and advanced encryption, the drone ensures protection against cyberattacks. Its modular and mobile design allows for adaptation to various environments, further improving enterprise resilience to cyber threats.

The third section includes the article ‘Method of Multidimensional Specification of the Role of Regions in National Economy Based on Entropy Analysis’ by Velichko and Polyakov. The authors highlight entropy analysis as a means to evaluate the sustainability and integration of regional economies within broader economic systems. They define three main types of entropy: economic diversification; income and employment distribution; and interregional ties. The authors also present a methodology for calculating entropy indicators using the generalized Shannon entropy formula. A comparative analysis of hypothetical regions reveals insights into regional development imbalances, and proposes strategies to enhance sustainability and diversification.

Population outflow is defined as a critical issue in the article ‘Formation of an Approach to Improving Regional Competitiveness in the Russian Federation’ by Kulkaev, which highlights the importance of attracting and retaining skilled individuals to strengthen regional economic systems. The author explores a three-stage model to increase regional competitiveness, focusing on building production foundations, developing science and education and fostering creative industries to promote socio-economic development and balance in the country.

The section ‘Management of Knowledge and Innovation for Sustainable Development’ includes the article ‘The Application of Ontology-Based Game Theory for Decision Support in Sociotechnical Systems’ by Gintciak, Burlutskaya, Zubkova, Uspenskiy. This study considers an invariant ontology of strategic interaction in a sociotechnical system using game theory tools. The research aims to create an ontology-based model of a sociotechnical system describing the interaction of social and technical elements through game interaction.

Irina Rudskaya, *Editor-in-Chief of SDEE Journal, Doctor of Economics, Professor*

TABLE OF CONTENTS

СОДЕРЖАНИЕ

SECTION 1

ECONOMICS OF ENGINEERING AND INNOVATION DECISIONS AS A PART OF SUSTANABLE DEVELOPMENT

РАЗДЕЛ 1

ЭКОНОМИКА ИНЖЕНЕРНЫХ И ИННОВАЦИОННЫХ РЕШЕНИЙ КАК ЧАСТЬ УСТОЙЧИВОГО РАЗВИТИЯ

Research article
DOI: https://doi.org/10.48554/SDEE.2024.3.1

Developing an Agile Project Management System with an Intellectual Module for Project Duration Prediction

Nikita Denisov, Aleksei Gintciak, Zhanna Burlutskaya, Darya Fedyaevskaya, Salbek Beketov*

Peter the Great St. Petersburg Polytechnic University, Saint Petersburg, Russian Federation,
aleksei.gintciak@spbpu.com, zhanna.burlutskaya@spbpu.com, darya.fedyaevskaya@spbpu.com,
salbek.beketov@spbpu.com
*Corresponding author: salbek.beketov@spbpu.com

Abstract

This paper describes the development of an agile project management system. This research is relevant because of the feature of agile projects consisting of changing requirements. We developed the architecture of the backlog and tasks management system, including a duration prediction module. Using the developed system, managers have the opportunity to divide project processes into sprints depending on the prediction and value for the stakeholders. The authors propose a method for predicting agile project duration by formalising the application of expert Story Point evaluation and subsequent Monte Carlo simulation. Based on the developed method, an algorithm for the dynamic prediction of task duration was designed. Integration of the developed method into the system made it possible to reduce the assumptions and limitations associated with updating user story data and participation in the projects of new and cross-functional teams. The developed system allows managers to cope with agile project bottlenecks.

Keywords: risk management, Monte Carlo simulation, Agile, project management system, decision support

Citation: Denisov, N., Gintciak, A., Burlutskaya, Z., Fedyaevskaya, D., Beketov, S., 2024. Developing an Agile Project Management System with an Intellectual Module for Project Duration Prediction. Sustainable Development and Engineering Economics 3, 1. https://doi.org/10.48554/SDEE.2024.3.1

Научная статья
УДК 005.8
DOI: https://doi.org/10.48554/SDEE.2024.3.1

Гибкая Система Управления Проектами с Интеллектуальным Модулем для Прогнозирования Продолжительности Проекта

Никита Денисов, Алексей Гинцяк, Жанна Бурлуцкая, Дарья Федяевская, Сальбек Бекетов*

Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Россия, aleksei.gintciak@spbpu.com, zhanna.burlutskaya@spbpu.com, darya.fedyaevskaya@spbpu.com, salbek.beketov@spbpu.com
*Автор, ответственный за переписку: salbek.beketov@spbpu.com

Аннотация

Статья посвящена разработке гибкой системы управления проектами. Актуальность исследования связана с особенностью гибких проектов, заключающейся в изменении требований. Авторами была разработана архитектура системы управления бэклогом и задачами, которая включает модуль прогнозирования продолжительности проекта. Таким образом, менеджеры имеют возможность распределять задачи по спринтам в зависимости от прогноза и ценности для заинтересованных сторон. Авторы предлагают метод прогнозирования продолжительности agile-проекта путем формализации экспертной оценки результатов и последующего применения моделирования методом Монте-Карло. На основе данного метода был разработан алгоритм динамического прогнозирования продолжительности проекта. Интеграция разработанного метода в систему позволила снизить его допущения и ограничения, связанные с обновлением данных пользовательских историй и участием в проекте кросс-функциональных и новых команд. Разработанная система позволяет справиться с узкими местами agile-проектов.

Ключевые слова: управление рисками, моделирование методом Монте-Карло, Agile, система управления проектами, поддержка принятия решений.

Цитирование: Денисов, Н., Гинцяк, А., Бурлуцкая , Ж., Федяевская, Д., Бекетов, С., 2024. Гибкая Система Управления Проектами с Интеллектуальным Модулем для Прогнозирования Продолжительности Проекта. Sustainable Development and Engineering Economics 3, 1. https://doi.org/10.48554/SDEE.2024.3.1

1. Introduction

Incorrect project duration estimation leads to a risk of time and material costs. In particular, such errors impact the ratio of a project's efficiency to its duration, i.e. its marginal utility. Overestimating a project's duration may convince managers to reject projects that would bring benefits and opportunities to the entity. Thus, errors of the second kind arise when researchers skip the correct hypothesis from consideration. Duration underestimation not only leads to the approval of projects that do not produce the expected results but also entails serious financial and reputational losses for the team (Morgenshtern et al., 2007). In such cases, an error of the first kind occurs because an incorrect prediction is accepted by a specialist.

The complexity of estimating project duration is highest for innovative projects characterised by a high level of uncertainty. Most projects related to software development belong to the category of innovative projects, which means they entail high management risks. Using an agile methodology to speed up the delivery of a product to the end user allows managers to change the requirements for the product during its development, which reduces transaction costs. Expertise with these tools is required to successfully estimate project duration. Such empirical estimates of duration are considered less reliable than algorithmic estimates (Morgenshtern et al., 2007). Existing mathematically formalised methods help managers numerically estimate project deadlines and performance.

For agile projects, there is a range of methods based on expert evaluation, such as Planning Poker, Bucket System, Dot Voting and consensus decision-making. It is difficult to identify the experts' subjectivity impact on them (Korytkowski and Malachowski, 2019); therefore, such empirical estimates are considered less reliable than algorithmic ones (Morgenshtern et al., 2007). In this regard, there is a need to formalise agile project scheduling methods by integrating classical expert methods with mathematical tools for prediction. Such a solution allows for the development of a tool for project risk management by increasing the accuracy of project duration prediction (Zachares et al., 2022).

Researchers are intensively investigating the issue of the project duration prediction, which is reflected by the number of approaches developed: network graphs (Critical Path Method (CPM; Kelley and Walker, 1959), Program Evaluation and Review Technique (PERT) (Gładysz, 2017), Graphical Evaluation and Review Technique (GERT) (Pritsker and Happ, 1966), Critical Chain Method (CCM; Aronson and Gerard, 1966; Goldratt, 1997; Leach, 1999)), machine learning (linear regression (Mahmoodzadeh et al., 2022), Gaussian process regression (Mahmoodzadeh et al., 2022), support vector regression (Acebes et al., 2015; Mahmoodzadeh et al., 2022), decision tree (Mahmoodzadeh et al., 2022), random forest (Acebes et al., 2015), genetic algorithms (Escandon-Bailon et al., 2021)), Monte Carlo method (Miranda et al., 2021; Monte Carlo Forecasting Analysis n.d.; Zachares et al., 2022; Zarghami, 2022), modifications of methods using fuzzy sets (García et al., 2010; Dubois et al., 2003), earned value management (Acebes et al., 2015; Barrientos-Orellana et al., 2021), a number of hybrid methods (Acebes et al., 2015; Islam et al., 2022). These techniques have different degrees of accuracy and applicability to flexible projects. However, studies reviewed do not take into account the main feature, which is the dynamic change in the requirements for the software product.

The research aims to develop a tool that allows for dynamically calculating the duration of individual tasks, the sprint backlog and the entire project. When designing the tool, we developed the architecture for a flexible project management system. The system architecture provides a module that predicts the duration of individual tasks in the backlog and the entire project based on user story data. The authors developed an algorithm for dynamic duration calculation based on this module. In this case, selecting a prediction method is required. Within the research, the existing mathematical approaches and methods of project scheduling (including their applicability to flexible project management) were analysed. Based on the analysed information, a modified approach to duration prediction was developed by combining expert evaluation of the SP complexity and Monte Carlo tasks. The method was tested on real data to compare its accuracy with alternative approaches' efficiency.

The developed method allows for point and interval estimation of the time spent on completing a set of tasks. The approach to the prediction module integration and the algorithm allows for the recalculation of task deadlines predictions. We also propose using a discreteness of recalculation equal to one sprint, which eliminates the risk of not meeting the time interval based on data about the past sprint. The developed method can be used in projects with an agile methodology working within the Scrum framework and using project management systems such as Jira, AirTable, YouTrack and GitLab. The method was tested on data from actual projects.

2. Materials and methods

2.1 Agile methodology

The features of the Agile Software Development methodology are 1) the use of iterative development, 2) dynamic formation of requirements, 3) ensuring their implementation as a result of constant interaction within self-organising working groups and 4) multidisciplinary working teams (Sosnin et al., 2015). Unlike agile methods, traditional approaches, such as the waterfall model, require strict planning in early stages, which makes them inappropriate for innovative projects, especially for fast-growing startups that are characterised by changing requirements and involve close contact with users (Kisielnicki and Misiak, 2017). The features of flexible projects related to the development of requirements often lead to failures. Thus, Rasheed et al. (2021) note that changing requirements are responsible for 12% of failures; incomplete requirements also cover 12% of the reviewed projects. In total, incorrect requirements management is responsible for 37% of failures.

The development of requirements determines the amount of work planned for the project (Wiegers and Beatty, 2013); therefore, plans, estimates and schedules should be developed on the basis of requirements. Agile development projects differ in that, in the initial stages, only high-level requirements are formed, usually as user stories, and during project implementation, requirements can change, adapt to new conditions, etc. (Wiegers and Beatty, 2013). Thus, the boundaries of the project are constantly changing, which entails uncertainty and difficulties in achieving adequate project planning. Despite its huge popularity, there is no clear conceptual definition and well-formalised methodological support for agile methodology (Szőke, 2011).

In practice, methods of estimating a project's size are used to form an idea of its duration. Although the literature does not identify an ideal indicator for software size estimation, the most commonly used indicators are the number of separately tested requirements; function scores; scores of user stories or use cases; the number, type and complexity of graphical user interface elements; and evaluations of code strings needed to implement specific requirements (Wiegers and Beatty, 2013).

The most popular set of practices and techniques used in projects with an agile methodology is the Scrum framework. Most entities that use an agile methodology for project management in one way or another use this management platform or some parts of it (e.g. ScrumBut; Moreira, 2013; Paasivaara et al., 2018). In this regard, this study is based on common practices widely used by entities and software development teams. The application of this method, in conjunction with existing practices, will ensure its seamless adoption by teams and entities for use as a formal way to evaluate project duration.

When using an agile methodology, especially within the Scrum framework, requirements are formulated in the form of user stories. This is a way of describing the requirements for the system being developed and formulated as one or more sentences in the user's everyday or business language. Unlike formulations with specific conditions and limitations, this approach allows the development team to evaluate the problem from different perspectives and independently find the best approach to find a solution (Rehkopf, n.d.). The task hereinafter refers to a unit of the work performed – i.e. a monolithic user story or a subtask of a composite user story.

All tasks fall into the general fund of tasks to be completed for project implementation. This is called the product backlog. Due to the peculiarities of working within the Scrum framework and agile methodology in general, the project can be called the current backlog (task set), while its duration is the duration of this task set. In addition to the project requirements, the backlog is updated dynamically, which means that it is supplemented with new tasks throughout the project and that some tasks may be removed due to irrelevance (Inayat et al., 2015; Raharjo and Purwandari, 2020; Rasheed et al., 2021). The backlog distribution by time depends on the task's importance, which is determined by its value to the customer and labour intensity (Inayat et al., 2015). When updating the list of tasks, their timing may change.

In contrast to the traditionally used man-hours, which allow for the creation a formal schedule (e.g. using a Gantt chart), Scrum uses special unformalised task evaluation units, which are called story points (SPs). They include the amount of work to be done, the labour intensity of the work and risks or uncertainty (Hamouda, 2014). It is important to note that SPs do not represent the required time, the number of strings in the code or the required specialist level but an arbitrary unit of empirically estimated complexity. SPs can be conceived of as comprehensive evaluations of labour intensity.

Despite the fact that SPs are widely used in development, they remain a subjective measure (Zahraoui and Idrissi, 2015). In addition, SPs are of no value to stakeholders who are not directly involved in development, while the estimation of a task's or entire project's duration in hours or days could be valuable information for them.

The transition from SPs to formalised metrics, such as hours or man-hours, will help understand whether the sprint backlog fits into the framework of the work resources (available man-hours) and estimate the entire project duration given current requirements (i.e. for the particular product backlog).

2.2 Approaches to prediction

There are several examples of SP formalisation in the scientific literature. For example, Abouelela and Benedicenti (2010) use a Bayesian network to model the process of extreme programming, which is another paradigm of agile development that includes SPs. Using the Bayesian network and several process parameters (team size, number of user stories, average labour intensity of the story, etc.) in two cases, the authors obtain formal indicators such as the number of days spent on the project and the number of strings in the code. Although the estimate of the time spent turned out to be quite close to the actual duration ($p < .09$), the authors noted the weak significance of other indicators. Additionally, the Bayesian network is a conceptually difficult model to understand and recreate.

Consider alternative methods of project duration mathematical prediction. Table 1 describes the various project duration prediction methods.

Table 1. Summary table of project duration prediction methods

Methods		**Description**	**Application for agile projects**
Network graph	Critical path method (CPM) Kelley and Walker (1959)	The project is represented as an activity diagram; the minimum project duration is a critical path.	-
	Program Evaluation and Review Technique (PERT) Gładysz (2017)	Probabilistic modification of CPM (taking into account the risk of delay).	-
	Graphical Evaluation and Review Technique (GERT) Pritsker and Happ (1966)	A network planning method that allows loops and returns and also contains Boolean operators.	+
	Critical chain method (CCM) Aronson and Gerard (1966), Goldratt (1997), Leach (1999)	A method that complements PERT with calculations based on resource dependencies, risks and uncertainties.	-

Machine learning (ML)	Linear regression (LR) Mahmoodzadeh et al. (2022)	An ML algorithm that is used to identify the influence of variables on the prediction.	+
	Gaussian process regression (GPR) Mahmoodzadeh et al. (2022)	A nonparametric ML algorithm divided into two parts: regression and classification.	+
	Support vector regression (SVR) Acebes et al. (2015), Mahmoodzadeh et al. (2022)	Characterised by kernels, sparse solutions and Vapnik-Chervonenkis (VC) control of the margin and the number of support vectors.	-
	Decision tree (DT) Mahmoodzadeh et al. (2022)	The Supervision learning algorithm repeatedly splits the sample based on specific questions about it.	+
	Random forest (RF) Acebes et al. (2015)	Nonparametric model composed of nodes and links in a hierarchical structure that can be used for classification or regression. Random forests are a technique for reducing variance in high-variance low-bias ML methods.	-
	Genetic algorithm Escandon-Bailon et al. (2021)	Adaptive search method used for optimisation purposes (evaluates the impact on the stability of adding new tasks).	+
Monte Carlo Zachares et al. (2022), Zarghami (2022)		A method of multiple simulation based on the indicator distribution and random number generation.	-
Modifications of methods using fuzzy sets (fuzzy-PERT) Dubois et al. (2003), García et al. (2010)		Modification of PERT using fuzzy sets; all calculations are similar but applicable to fuzzy numbers.	+
Earned value management (EVM) Acebes et al. (2015), Barrientos-Orellana et al. (2021)		Method of project monitoring and control based on the ‘time-cost-productivity’ dependence.	-
Hybrid methods	EVM + Monte Carlo Acebes et al. (2015)	For every realisation of a Monte Carlo simulation, the system provides a final cost and time. That is, when the percentage of completion of a simulation is 100% (x = 100%), we obtain the final cost (c100%) and final duration for that simulation (t100%). This triad (100%, t100%, c100%) gives this methodology its name.	+
	EVM + Monte Carlo + classifier algorithm Acebes et al. (2015)	Hybrid model of combined EVM, Monte Carlo and classification algorithm for calculating performance from duration and cost.	+
	Genetic algorithm + Monte Carlo Islam et al. (2022)	Hybrid predictive-probabilistic-based model (HPPM) for calculating the probability of resource overruns.	+

Let us consider the prospect of using network graphs in agile projects. The CPM describes a project as a network graph in which nodes represent events and arcs represent tasks to be performed (Kelley and Walker, 1959). Analysts use this method to calculate the minimum project completion time and the early and late deadline for each task. To use this method, clear time limits for each task must be known, and the project management plan should be indicated in advance. Thus, this method cannot be applied to projects with an agile methodology due to their dynamic requirements and returns to previous stages. Unlike deterministic CPM, PERT is a stochastic method. For each task, a pessimistic, optimistic and realistic estimate of the execution time is indicated. Based on the beta distribution of a special form (Gładysz, 2017), a probabilistic estimate of the project duration is calculated, which makes it possible to calculate the global risks of delay. This method also assumes a strict structure and project plan, so it cannot be implemented for agile development projects. Another analogue of the network graph method is the GERT tool. It allows loops and returns in the operation execution scheme and contains Boolean operators: AND (all operations must be performed), OR (at least one operation must be performed) and XOR (only one operation can be performed). The operational events can be both probabilistic (e.g. there is some chance of an operation fixing a bug) and deterministic (e.g. the operation will be performed with a probability of 1; Pritsker and Happ, 1966). Thus, although GERT can be regarded as a more flexible tool, this flexibility complicates the diagram and algorithm for evaluating the project as a whole. The CCM is based on the methods and algorithms of constraint theory. In contrast to CPM and PERT, it does not involve a rigid sequence of tasks and rigid planning. Instead of deadlines for tasks, CCM focuses on ensuring the completion of the entire project as soon as possible. It requires task performers to be flexible with respect to task start times and quickly switch between tasks to keep the entire project on schedule (Goldratt, 1997). The use of CCM helped reduce the time spent and the cost of projects by 10–50% compared to traditional methods (PERT, CPM and Gantt charts) (Leach, 1999). However, this method assumes resource inexhaustibility, which prevents its use in agile projects.

One way to cope with the limitations of the classical formal setting of scheduling tasks is through the use of flexible constraints in planning (Dubois et al., 2003). The application of fuzzy set theory makes it possible to eliminate uncertainty and take local preference specifications into account (Dubois et al., 2003). Fuzzy methods aim to find reliable schedules in which all constraints are satisfied to some extent with a sufficient confidence level. Wiegers and Beatty (2013) point out that the best processes for estimating project duration take into account the uncertainty and constant variability of project boundaries. Fuzzy set theory is also used in conjunction with the PERT method. In the standard version, most of the parameters of interest are obtained via simple algorithms, including addition, subtraction, minimums and maximums. In the modified version, the same calculations can be performed, turning numbers into fuzzy numbers using the results of fuzzy arithmetic (Dubois et al., 2003). However, the fuzzy-PERT method is not generic for all projects. Moreover, because the method is labour intensive and difficult to develop, generating predictions for individual projects takes too long.

Machine learning (ML) methods, including linear regression (Mahmoodzadeh et al., 2022), Gaussian process regression (Mahmoodzadeh et al., 2022), support vector regression (SVR; Mahmoodzadeh et al., 2022), decision tree (DT; Acebes et al., 2015), random forest (RF; Mahmoodzadeh et al., 2022) and genetic algorithms (Mahmoodzadeh et al., 2022) are also used to estimate project duration. Linear regression (LR) is an ML algorithm based on supervised learning that is used to determine the relationship between variables and prediction (Mahmoodzadeh et al., 2022). Regression models are target prediction values based on independent variables. Gaussian process regression (GPR) is a nonparametric ML algorithm based on supervised learning divided into two major groups: regression and classification. GPR has shown an excellent ability to solve various problems with a small amount of data (Mahmoodzadeh et al., 2022). SVR is characterised by kernels, sparse solutions and Vapnik-Chervonenkis (VC) control of the margin and the number of support vectors (Mahmoodzadeh et al., 2022). One of the main advantages of SVR is that its computational complexity does not depend on the dimensionality of the input space (Mahmoodzadeh et al., 2022). It performs smaller calculations than other regression methods. DTs are supervision learning algorithms that repeatedly split samples based on specific questions about them. They are useful for prediction problems (Mahmoodzadeh et al., 2022). This method identifies the most significant variables and the relationships between two or more variables. Tree models are robust and straightforward to interpret (Acebes et al., 2015). However, they cannot handle high-variance samples (Acebes et al., 2015). Project duration prediction is also carried out using genetic algorithms. Project duration is considered a function of efficiency and stability (Escandon-Bailon et al., 2021). Efficiency refers to project duration and cost. Stability is the difference in the distribution of tasks between the initial schedule and rescheduling. The experimental study considers the addition of 4/8/12 new tasks. The authors concluded that the fewer tasks there are, the greater the impact on stability. Another conclusion was that the arrival of new team members does not shorten a project's duration but rather increases its cost. Neural networks have achieved state-of-the-art results in a number of prediction tasks (Zachares et al., 2022). Zachares et al. (2022) set the task of duration prediction as a multiclass classification problem for training neural networks to obtain a histogram distribution describing the uncertainty in duration tasks at the output. Machine learning models and neural networks are often called ‘black boxes’ because of the difficulty in interpreting intermediate results.

Earned value management (EVM) is the most popular managerial methodology used in project management (Acebes et al., 2015). This framework integrates, via a unified approach, three dimensions of the project – scope, time and cost – using monetary units as a common pivotal measure. EVM is based on the integrated master schedule (IMS) tool. It is built on the basis of project control points and a responsibility assignment matrix. Upon completion of an IMS, a project’s budget is developed by the manager according to the time costs of each stage and substage. Based on the EVM method, the time and monetary costs of the project are predicted based on the existing trends of these indicators within the project. Since it is necessary to define a task list to schedule and predict project duration, EVM cannot be applied to innovative projects using agile development methods.

Another tool used for project duration planning is the Monte Carlo method. It assumes multiple simulations, which is the generation of a task duration sample according to a given distribution. Instead of giving a known estimate for the task set duration, it is calculated for each of the hundreds or thousands of simulations. As a result, we can obtain not only an estimate but also a probability distribution for the project duration. In addition, the Monte Carlo method seems to be more understandable and easily explained to laymen than mathematical algorithms and regression analysis.

The Monte Carlo method is used both for projects applying traditional development methods and those using agile methodologies. The input data needed to use this method are the time spent on tasks and the execution of one user story (Miranda et al., 2021; Monte Carlo Forecasting Analysis, n.d.; Zachares et al., 2022). Researchers use various options to determine the time spent, the cost of executing one user story (Miranda et al., 2021) and the interval between the completion dates of tasks (Monte Carlo Forecasting Analysis n.d.; Zachares et al., 2022).

2.3 Method development

The application of the Monte Carlo method to predict project duration is described in detail in this section (Monte Carlo Forecasting Analysis, n.d.). In this study, project duration is predicted based on the takt time. In a production line, the takt time is the period within which the manufacture of each product is completed. Knowing the takt time, the manufacturer can run the line at a speed corresponding to demand. In terms of agile project management, takt time is represented as the period between the completion of user stories. The authors calculate the time between task completion dates (i.e. the time within which tasks were not completed) to determine the delivery rate. Due to the takt time, it is possible to predict the time required to complete a task or project.

The input data required for this method are datasets consisting of user stories, the confidence interval and the number of tasks to predict. A user stories dataset includes completed tasks and their start and completion dates. The takt time is calculated based on these dates. Applying the Monte Carlo method consists of repeatedly modelling a possible situation via a random variable generator. Then, based on the data obtained, the probabilistic characteristics of the process under consideration are calculated.

In this paper, the Monte Carlo method is used to predict project duration via multiple simulations. A random value of the project duration is calculated, including its pessimistic, median and optimistic estimates at a given confidence interval $[a,b]$. However, the proposed method differs from the above method in the following ways:

1. Takt time is replaced by a calculation of task complexity, which is determined by transferring expert evaluations of labour intensity from SPs to man-hours. The time required to complete the project is then determined based on the calculated labour intensity and the known working fund.

2. The use of random values from the user stories dataset is replaced by the selection of a continu-

ous distribution function *G(x)* reflecting user story data with known accuracy.

Thus, the dataset of user stories includes completed tasks, their expert evaluation of labour intensity in SPs and the real time spent on execution.

Since expert evaluation in SPs is an informal assessment, it can vary depending on the entity, project or task. Thus, the SP cost cannot be assigned a specific value, and the use of an average or median value is impracticable. However, it is possible to represent the SP cost as a random variable with some distribution. The 'raw' array *SP Cost* is actually a sample for some sample $\tilde{G}(x)$ distribution function of the SP cost.

According to the Glivenko–Cantelli theorem, the sample $\tilde{G}(x)$ distribution function almost converges on its theoretical counterpart *G(x)* when the sample size increases. At the same time, the sample distribution function values are limited and depend on the amount of user story data. Removing the function's discreteness increases the data's accuracy, so instead of using random values from a sample distribution function over an array *SP Cost*, this function is approximated by a continuous distribution function *G(x)*.

A total of 106 various distributions are available to the algorithm, particularly an array of 10 distributions that are called common (normal, generalised normal, log-normal, power law, uniform, exponential, gamma, chi-squared and Rayleigh-Cauchy). The algorithm goes through the popular (or all) distribution functions and uses the Levenberg–Marquardt algorithm (Levenberg, 1944) to select parameters at which the function is as close as possible to the sample distribution. Then, based on the least squares method, the most appropriate distribution is selected, denoted above as *G(x)*.

Thus, based on user story data, a distribution function *G(x)* that reflects the random nature of the SP cost is calculated. For a future th task, one can calculate its labour intensity by multiplying the SP cost by the SP quantity in the expert evaluation:

$$Effort_i = SP\ Cost \text{ x } SP_i \tag{1}$$

For each *j*th simulation, the labour intensity of the *i*th task is calculated as follows:

$$Effort_{ij} = rand(G(x)) \text{ x } SP_i \tag{2}$$

where *rand(G(x))* is a random number generated by the approximating cost distribution function *SP G(x)*, *j* is the Monte Carlo simulation number (j = 1, ..., R) and R is the number of simulations.

Then, for each th simulation, the labour intensity of the project as a set of N tasks is the sum of the labour intensity of these tasks:

$$T_j = \sum_{i=1}^{N} Effort_{ij} = \sum_{i=1}^{N} rand(G(x)) \times SP_i \tag{3}$$

Such a sum calculates a given number R times (in this paper, R = 10,000), forming a random variable represented by some array. It is a probabilistic assessment of the project labour intensity in units of labour – man-days, man-hours or (more often) man-seconds, depending on the source data format. A more convenient interval and point estimate can be obtained from it. The interval estimate is a confidence interval $[T_a,T_b]$, where T_a is the *a*th percentile (lower, optimistic estimate) and T_b is the *b*th percentile (upper, pessimistic estimate). In this paper, we consider a 90% confidence interval such that a = 5 and b = 95. The point estimate represents the 50th percentile (median of the sample). Thus, the algorithm returns an optimistic, median and pessimistic estimate of labour intensity: T_5, T_{50} and, T_{95}, respectively.

Explain the concept of the team's working time fund, which is the available number of labour units (man-days, man-hours or man-seconds) for a certain period. Basically, if all employees are able to work on tasks, and the amount of working time is fixed, then the team's working time fund is calculated as follows:

$$Resource = Labour \text{ x } Availability \tag{4}$$

where *Labour* is the number of employees working on tasks and *Availability* is the number of labour time units over the time interval.

For instance, if a team of five people works 40 hours a week on tasks, then the team's working time fund will be 200 man-hours per (working) week. If the number of working hours of employees varies, then the working time fund of the team of M employees is calculated as follows:

$$Resource = \sum_{1}^{M} Availability_i \tag{5}$$

where *Availability* is the number *i* of the employee's working time units.

To predict a project's duration, it is necessary to divide the labour intensity estimate by the team's working time fund. Thus, we can obtain an optimistic, point-based and pessimistic estimate of the project's duration:

$$D_o = T_5/Resource \tag{6}$$

$$D_m = T_{50}/Resource \tag{7}$$

$$D_p = T_{95}/Resource \tag{8}$$

For instance, if the working time fund of the team is man-hours per week, and the labour intensity of the project is estimated as T_5 = 400, T_{50} = 600, and T_{95} = 1,000 hours, then the interval estimate of the project duration will be an interval [D_o,D_p] = [400/200,1000/500] = [2,5], from 2 to 5 weeks, and the point will be D_m = 600/200 = 3 weeks.

Thus, the method implementation follows the following algorithm:

1. Reading user story data from a CSV file (task *Issue*, expert evaluation *SP*, time spent *Time Spent*)

2. Calculation of the user story SP cost for each completed task *SP Cost = Time Spent / SP*:

3. Approximation of the sample via a *SP Cost* continuous distribution function *G(x)*

4. Multiple random generation of SP cost for future probability distribution tasks *G(x)*:

SP Cost = rand(G(x))

5. Calculation of the possible labour intensity of tasks as the product of the generated cost for their expert evaluation *Effort = SP Cost* x *SP*:

6. Calculation of the project labour intensity as the sum of the labour intensity of the corresponding tasks for each iteration: $T = \sum_{1}^{N} Effort_i$

7. Calculation of optimistic, median and pessimistic estimates of labour intensity based on the samples obtained after repeated simulation: T_a, T_{50}, T_{95}

8. Calculation of the optimistic, median and pessimistic duration estimates as the ratio of the labour intensity estimate to the team's working time fund: $D_a = T_a/Resource$, $D_{50} = T_{50}/Resource$, $D_b = T_b/Resource$

Figure 1 shows a visual representation of the algorithm.

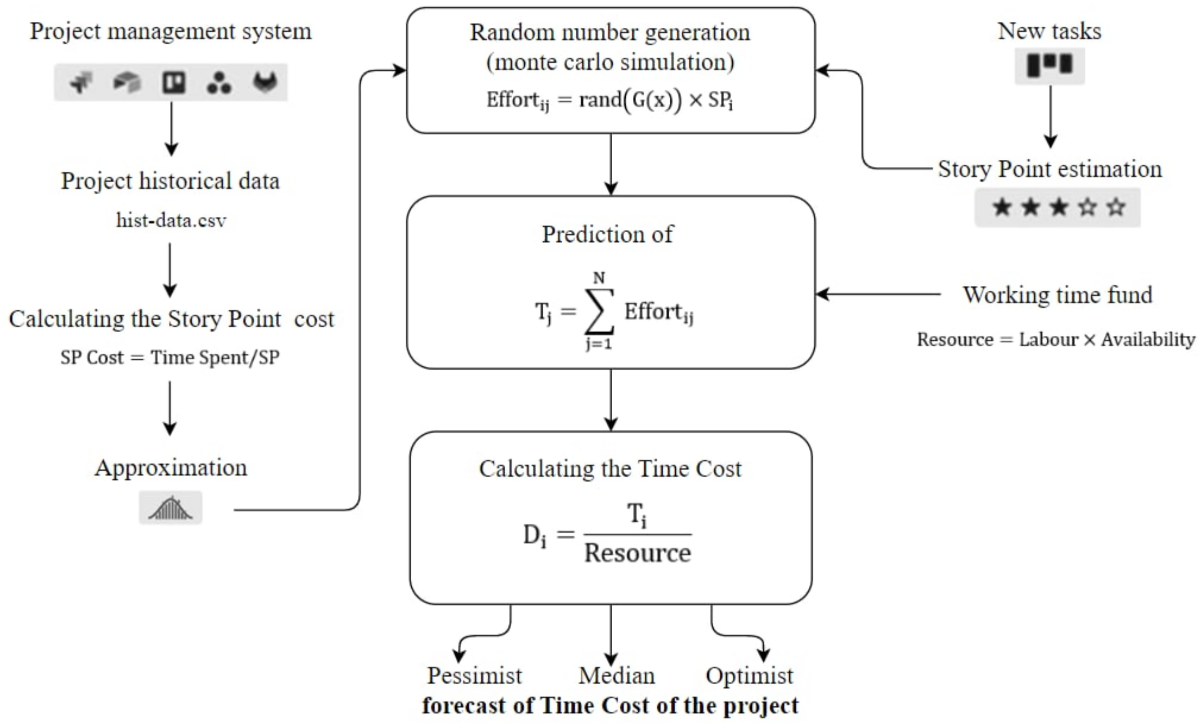

Figure 1. Algorithm

The algorithm has the following parameters:

1. Any array column representing the names of user story data columns with unique task names, expert estimates in SP and known time spent (the column names may vary in different systems, so the algorithm can be adjusted to specific well-established column names)

2. The confidence interval boundaries (low and high), which represent quantiles

3. The number of Monte Carlo simulation repeats

4. The random number generator seed

5. Boolean value log (logs to a file if true)

6. Boolean value plot (saves a graph with the SP cost histogram and continuous distribution functions if true)

7. Boolean value for all distributions (approximates the SP cost sample using all available distributions if true)

8. Object found distribution (allows using a known distribution instead of performing the approximation procedure; if logging is enabled, the appropriate distribution will be recorded in the log file and can be reused)

9. Working time fund resource

The method was implemented using a Python algorithm. The proposed approach can use generalised user story data from different teams, but since SP is an empirical estimate, the approach will give increased accuracy when using fresh user story data for a specific team as input. Such data can be downloaded from project management software, including commonly used systems such as Jira, YouTrack and GitLab.

3. Results

3.1 Architecture of a dynamic system for predicting task duration in a flexible development project

Projects using flexible management techniques clarify requirements throughout their duration (Inayat et al. 2015; Rasheed et al. 2021). After a task is added to the product backlog and prioritised, the possibility of adding it to one of the sprints must be addressed. Thus, each time a task is added, a prediction of its execution and the entire project duration must be made.

In addition, the feature of project management lies in the participation of cross-functional teams that gather in different combinations of specialties depending on the project. For instance, when compiling a new combination of employees, user story data on the performance of their tasks will be missing. In such cases, the following recalculation algorithm can be applied: The duration prediction of the tasks performed by the team is made in accordance with the distribution selected based on all the company's projects. Thus, this distribution represents the median value. Throughout the project, the data is updated, and the prediction is adjusted depending on the gaps between the median value and the actual performance of the team.

To solve these problems, a tool that allows for updating data on project management and team performance needs to be designed. Within the task, we propose combining the developed method of project duration prediction with task tracking tools.

To design a task management system and a backlog for a flexible project that includes a duration prediction module, the widespread Jira system became the foundation. Then, a backlog management module was incorporated. This allowed for the distribution of tasks depending on the predicted value of their duration and value determined when the task was listed (Figure 2). A Monte Carlo simulation module was also introduced. It included algorithms for predicting the duration of tasks and the project.

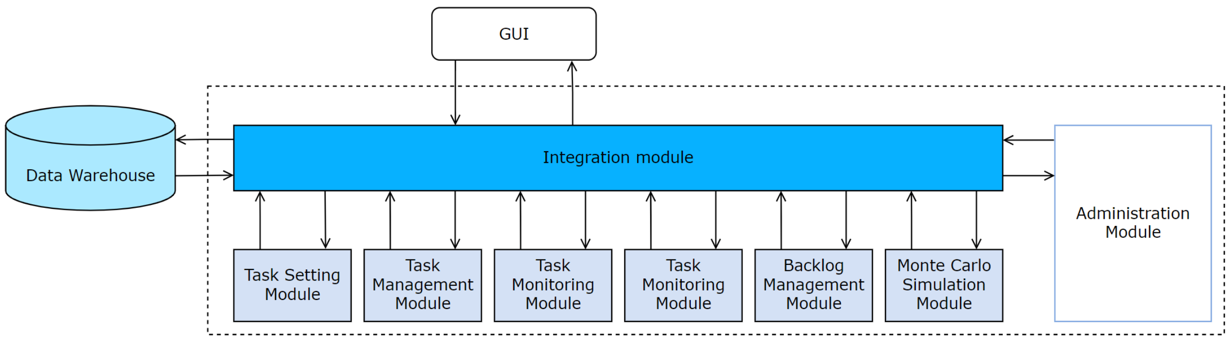

Figure 2. Architecture of a task management system with a prediction module

3.2 Prediction method

Two indicators were selected as metrics of the method's effectiveness:

1. The percentage of projects whose duration was correctly predicted by the interval estimate (the project duration lies between the optimistic and pessimistic values), which is hereinafter denoted as the prediction accuracy.

2. The mean magnitude of relative error (MMRE)

As part of testing, it is necessary to compare the estimate's and labour intensity's actual values, not the project duration, since the duration estimate for a single team linearly depends on the team's working time fund. At the same time, the real working time fund is unknown for the teams and can only be accepted with large assumptions. Since in this case the main features of this work (taking into account expert evaluation and calculating the SP cost and its approximation via a continuous distribution function) affect labour intensity, it was agreed to calculate efficiency metrics specifically for estimating labour intensity.

3.3 Data for testing

The data source for testing the method is exported project data from the most popular project management system, Jira (Datanyse, n.d.; Sense, n.d.). However, if the relevant data are available, it is possible to work with uploads from other systems (Airtable, Trello, Asana or YouTrack).

The following set of tasks with two known parameters is sufficient as user story data for a project:

1. Expert evaluation of the task's labour costs in SPs

2. The actual fixed duration of the task in time units

In long-term projects, teams typically changes over time; new employees come and old ones leave. Managing personnel (project managers and scrum masters) are also subject to changes, and methods of estimating labour costs can be modified over time. Thus, it is reasonable in some cases to use several recent tasks or tasks over the latest period as user story data (the sliding window technique). For instance, the time of task creation can be used as user story data for such modifications.

Data from APACHE (n.d.), Atlassian (n.d.), Hyperledger (n.d.), Mongo (n.d.), Qt (n.d.), and Red Hat (n.d.) projects were used in the experiment. Before uploading, the task data were filtered to meet the following conditions:

1. The task is completed (has a Resolved, Closed, Done, etc., status, depending on the project).

2. The task has a known labour cost estimate.

3. The actual duration of the task is known.

This method does not require preliminary data processing if the conditions described above are satisfied, except in cases of estimating the labour costs of tasks in nonnumeric form Deltamatrix (n.d.). If the task estimates are nonnumeric, then they are converted into natural numbers, where 1 SP corresponds to the minimum estimate of labour costs, 2 SPs corresponds to the next level of labour intensity, etc., or, according to a custom conversion formula if the labour intensity increases nonlinearly from level to level. For example, in the CAMEL project, labour costs were estimated by difficulty levels: novice, moderate and advanced. After unloading, these estimates were translated into 1, 2 and 3 SPs, respectively.

In addition, the algorithm user needs to ensure that in the uploaded CSV file, the column with the unique task name is called Issue, the column with the expert evaluation is called SP and the column with time spent is called Time Spent. If not, the user can change the column names directly in the data file or in the algorithm parameters.

Initially, there were six entities, 24 projects and more than 1,400 tasks in the dataset. Some projects contained too few tasks to build a distribution and a correct estimate; therefore, to preserve the representativeness of the sample, they were deleted or combined with other projects of the same entity that were carried out in the same period and that had a close average ratio of the estimate to the time spent *(SP / Time Spent)*.

Thus, the initial data for the scientific experiment are represented as 15 projects consisting of a total of 1,373 tasks:

1. APACHE projects: CAMEL (83 tasks), MXNET (72 tasks), HUDI (28 tasks)

2. Atlassian project: CRUC (41 tasks)

3. Hyperledger projects: BE (27 tasks), FAB (16 tasks)

4. Mongo projects: EVG (649 tasks), DOCS (11 tasks)

5. Qt project: QT (14 tasks)

6. Red Hat projects: RHODES (128 tasks), TEIID (121 tasks), JBEAP (71 tasks), TEIIDSB (53 tasks), MULTIARCH (40 tasks), ODC (19 tasks)

3.4 Results of numerical experiments

User story data were randomly divided into two groups: a training sample (70%) and a control sample (30%). Each contained a task set with the following parameters for each th task:

1. The name of the project to which the task belongs (*Project*)

2. The key – the unique name of the task (*Issue*)

3. An estimation of labour costs in SP (*SP*)

4. The time spent completing tasks (*Time Spent*)

5. The calculated parameter – the cost of one SP in time units (*SP Cost = SPi / Time Spent*)

Since the validation data with information about the tasks were de facto user stories, their real labour intensity was known to them. The task set duration was the sum of these values, i.e. the actual labour intensity of *T* project for *N* tasks was calculated as follows:

$$T = \sum_{1}^{N} Time\ Spent_i \tag{9}$$

where $Time\ Spent_i$ is the real duration of the *i*th task.

In this paper, this duration is compared with the prediction obtained via the method under consideration. To test this method, two performance metrics were determined at the level of estimating the duration of a single task set. The first was a Boolean value, which was the very fact that the actual duration *T* falls into the predicted interval $[T_5, T_{95}]$(at $a = 5$, $b = 95$ percentiles):

$$In\ Range \begin{cases} 0, T \notin [T_5, T_{95}] \\ 1, T \in [T_5, T_{95}] \end{cases} \tag{10}$$

The second was the relative error of the point estimate, calculated as follows:

$$RE = \frac{T_{50} - T}{T} \tag{11}$$

Using the algorithm, a CSV file was created in which the estimates and performance metrics were recorded for each of the 15 projects (Table 2).

Table 2. Content of the resulting file

Project	Data points	Time Spent	Estimation	Error	Relative Error	Score (from 0 to 5)	Range	In Range	Range Size	ARE
EVG	195	387	362	-25	-7%	5	[320 – 458]	+	138	7%
RHODS	38	1051200	737658	-313542	-30%	4	[589158 - 886117]	-	296959	30%
TEIID	36	518100	496206	-21894	-4%	5	[410744 - 598454]	+	187710	4%
CAMEL	25	41400	39729	-1671	-4%	5	[38200 - 46287]	+	8087	4%
MXNET	22	36600	310287	-56313	-15%	5	[182171 - 621453]	+	439282	15%
JBEAP	21	1306920	2089532	782612	60%	3	[1057600 - 4898303]	+	3840703	60%
TEIIDSB	16	264600	174556	-90044	-34%	4	[98425 - 251182]	-	152757	34%
CRUC	12	40740	48147	7407	18%	5	[26218 - 138157]	+	111939	18%

MULTIARCH	12	1238400	834348	-404052	-33%	4	[162951 - 1501340]	+	1338389	33%
HUDI	8	34500	83051	48551	141%	0	[37824 -129551]	-	91727	141%
BE	8	331500	426002	94502	29%	4	[238608 - 1007097]	+	768489	29%
ODC	6	439200	306900	-132300	-30%	4	[153663 - 639472]	+	485809	30%
FAB	5	496800	145633	-351167	-71%	2	[-404324 - 714211]	+	1118535	71%
QT	4	403200	600144	196944	49%	3	[115048 - 1089692]	+	974644	49%
DOCS	3	36	6	-30	-84%	1	[4 – 29]	-	25	84%

The method's effectiveness at the level of the project labour intensity prediction was also determined using the following metrics: the accuracy of hitting the confidence interval (5–95%) and the MMRE:

$$Accuracy = \frac{1}{M}\sum_{1}^{M} In\ Range_j \tag{12}$$

$$MMRE = \frac{1}{M}\sum\nolimits_{1}^{M}|RE| = \frac{1}{M}\sum\nolimits_{1}^{M}\frac{|T_{50} - T|}{T} \tag{13}$$

For all 15 projects, we obtained an accuracy of around 73% and an MMRE of around 41%. However, it should be noted that significant outliers are typical for projects with a small number of tasks (i.e. eight or fewer), which means that the training sample comprises up to 19 tasks. When we excluded these tasks, the accuracy of hitting the interval increased slightly to around 78%, but the MMRE dropped significantly to around 23% (Table 3). Therefore, it is recommended that this method be used with at least 20 tasks in the training user story data.

Table 3. Comparison of forecast accuracy

	For all	For 20+ tasks
Count	15	9
Datapoints	411	377
MMRE	41%	23%

When this condition was met, the accuracy was comparable to the implementation of the Monte Carlo method described in (Miranda et al. 2021), which had an accuracy of 80%; however, the MMRE decreased from around 32% to 23% with a similar amount of training data – on average, 104 tasks in Miranda et al.'s (2021) study and 112 tasks in this study.

As expected, there was an increase in the prediction effectiveness for the selected indicators with 20 or more tasks as user story data, while the relative error increased noticeably on small training samples. Therefore, the method is not recommended for use with a small number of completed task estimates.

The increase in the MMRE has also been confirmed on data in which the SP cost has a large spread, including on projects where expert estimates of the labour intensity of simple tasks are overestimated, while expert estimates of the labour intensity of complex tasks are underestimated. Thus, the correctness of the evaluation of tasks by experts naturally affects this method's accuracy.

3.5 Assumptions and limitations

It is assumed that the main limitation of the developed prediction method is the minimum amount of user story data that the algorithm needs to show satisfactory indicators of prediction efficiency. With insufficient user story data, the sample distribution is overly influenced by outliers, which means that both the sample SP cost distribution function and its continuous analogue do not reliably reflect the actual SP cost distribution. For this reason, the method is a poor choice for predicting project duration for recently formed teams (Raharjo and Purwandari 2020) or those that have just started using the Scrum framework and evaluating tasks in SPs.

As expected, a correct expert evaluation of the task labour intensity in SP units helps the team calculate their strength for the sprint and the project as a whole. For an experienced team and experts, such an evaluation becomes more accurate, and the SP cost varies less from task to task; simply put, the sample from the SP cost for each task has a smaller variance. It follows that the possible labour intensity of the tasks will be closer to their mathematical expectation, and with a high probability, the estimation error will decrease. However, on data where the SP cost depends on a particular task, the prediction error will be higher. An incorrect labour-intensity expert evaluation of tasks will lead to erroneous predictions, both when using this method and when using only expert evaluation without applying mathematical tools.

The SP cost can also vary due to the different skill levels of employees. A professional employee tends to complete a task estimated at 1 SP of difficulty faster than an intern. Korytkowski and Malachowski (2019) take competencies into account when assessing project duration with agile management.

This method has the potential for modification and expansion. Because of the available structure, it is easier to scale than systems such as neural networks or Bayesian systems. There is reason to believe that an increase in the quantity of input data (employee competencies, variable working hours, multiple estimates of labour intensity, user story data, etc.) will further reduce the prediction deviation from the actual deadlines.

The proposed method is promising for joint use on a group of projects to balance the distribution of labour resources between projects. In addition, the input data are the user story data for each individual project. To do this, you need to find (eq. 14) such that (eq. 15).

$$Resource = [Resource_1, \dots , Resource_5] \tag{14}$$

$$\max(T_i) = \max\left(\frac{Effort_i}{\mathrm{Re}\,source_i}\right) \to \min \tag{15}$$

3.6 Dynamic prediction algorithm

Based on the designed module, an algorithm for the entire system operation was developed (Figure 3). The task-setting module and task-management module supply data to the warehouse. Thus, data on the task type, SP and team are added, and data on the task execution time are updated. Data are requested from storage by the Monte Carlo simulation module with an assigned slot for prediction recalculation. We propose using a recalculation slot equal to one sprint. In this case, before the sprint start, data on completed tasks, including technical debt, will be entered, and new tasks allocated during the sprint are entered. Updated data on the task duration allows for redistributing the sprint backlog so that there are no delays. The prediction results are sent to the backlog management module, where they are shown to the user.

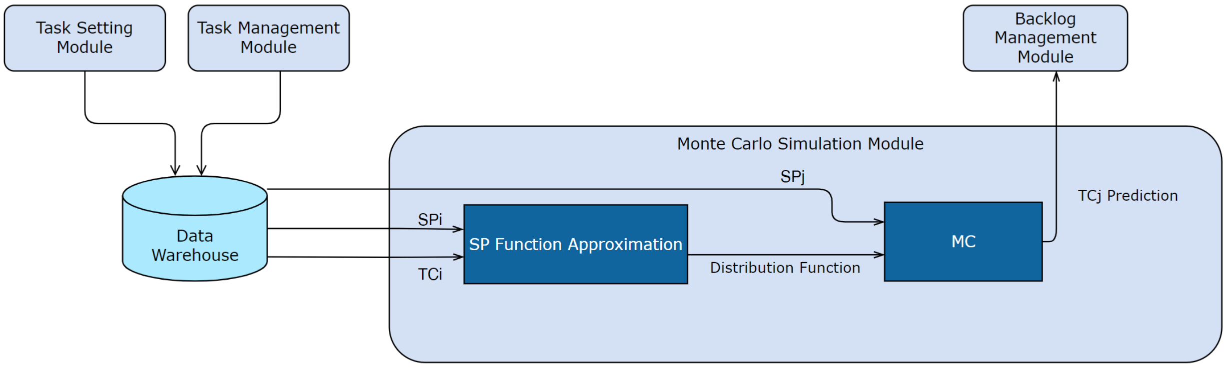

Figure 3. System algorithm

4. Discussion

The existing approaches to calculating project time costs were used as input data: the cost of performing one user story [16] and the interval between the completion dates of tasks [6],[17]. The authors propose the use of a heuristic evaluation of tasks in the SP form. This allows for taking advantage of the assessment, meaning that the SP assessment reflects a similar labour intensity for different tasks.

In contrast to the use of time cost point estimates [6],[16],[17], the proposed method recommends the application of a user story data distribution function, which is selected by a built-in algorithm. Thus, multiple simulations of random numbers (Monte Carlo method) are executed according to a continuous distribution function rather than a limited quantity of user story data. Thus, the accuracy of the Monte Carlo method was improved without increasing the input data sample.

The output data of the developed method is a pessimistic, median and optimistic prediction of the project duration. Interval estimation of the project duration allows for establishing pessimistic deadlines for critical tasks and projects and assessing the risks of failure to conclude contracts.

To reduce the impact of the developed method's limitations and assumptions, we proposed designing a tool for managing tasks and the product backlog in flexible projects. The main limitation of the method – low quantity of user story data – decreased throughout the project. For the initial assessment, we recommend using the entire company's data, after which the assessment is adjusted depending on the added values. Likewise, the assumption of cross-functional teams participating in the project, which are formed in such a composition for the first time [2],[24], is eliminated.

An architectural approach to building a system through a control module will allow for scaling of the system, including connecting additional modules. As part of the consideration of the possibilities of scaling the entire system of setting and tracking tasks, a system of employee incentives can be developed based on the labour productivity that they showed when performing tasks from the backlog.

Dynamic prediction allows for taking into account new tasks in the backlog and redistributing them across sprints depending on their value and the required labour costs. This system application also has prospects for the redistribution of labour costs between projects.

5. Conclusion

The authors managed to develop an architecture model of a flexible project management system. The system includes a model for predicting the duration of both individual tasks and the entire project. It is designed to eliminate the problems of meeting deadlines associated with changing requirements throughout the project.

A modified duration prediction method was chosen based on the joint use of SP expert evaluation and the Monte Carlo method. The developed tool allows for point and interval estimation of the time spent on completing a task set. It can be used in projects with an agile methodology working within the Scrum framework and using project management systems such as Jira, AirTable, YouTrack and GitLab. The developed method has been verified on data from real projects using agile methodologies (APACHE, Atlassian, Hyperledger, Mongo, Qt and Red Hat). The experimental results demonstrate the advantage of the developed approach over the Monte Carlo method without expert evaluation and expert evaluation by itself.

The developed method was implemented in the architecture of the task management system and the backlog. The authors developed an algorithm for the dynamic calculation of task duration. This method integration will reduce limitations due to low quantity user story data and the complexity of cross-functional tasks. The architectural approach will allow for scaling the system. Dynamic recalculation of task and project duration prediction will eliminate the risks of not meeting deadlines due to the prediction and new requirements, among other things. This allows for taking into account the feature of a flexible project consisting in dynamically updated requirements.

Acknowledgements

The research is funded by the Ministry of Science and Higher Education of the Russian Federation (contract No. 075-03-2024-004 dated 17.01.2024).

References

Abouelela, M., Benedicenti, L., 2010. Bayesian network based XP process modelling. International Journal of Software Engineering & Applications 1 (3), 1–15. https://doi.org/10.5121/ijsea.2010.1301.

Acebes, F., Pereda, M., Poza, D., Pajares, J., Galán, J.M., 2015. Stochastic earned value analysis using Monte Carlo simulation and statistical learning techniques. International Journal of Project Management 33 (7), 1597–1609. https://doi.org/10.1016/j.ijproman.2015.06.012.

Aronson, E., Gerard, E., 1966. Beyond Parkinson's Law: the effect of excess time on subsequent performance. Journal of Personality and Social Psychology 3 (3), 336–339. https://doi.org/10.1037/h0023000.

Barrientos-Orellana, A., Ballesteros-Pérez, P., Mora-Melia, D., González-Cruz, M.C., Vanhoucke, M., 2021. Stability and accuracy of deterministic project duration forecasting methods in earned value management. Engineering, Construction and Architectural Management 29 (3). https://doi.org/10.1108/ECAM-12-2020-1045.

Dubois, D., Fargier, H. Fortemps, P., 2003. Fuzzy scheduling: modelling flexible constraints vs. coping with incomplete knowledge. European Journal of Operational Research 147 (2), 231–252. https://doi.org/10.1016/S0377-2217(02)00558-1.

Escandon-Bailon, V., Cervantes, H., García-Nájera, A., Zapotecas-Martínez. S., 2021. Analysis of the multi-objective release plan rescheduling problem. Knowledge-Based Systems 220, 106922. https://doi.org/10.1016/j.knosys.2021.106922.

García, C.B.G., Pérez, J.G., Rambaud, S.C., 2010. Proposal of a new distribution in PERT methodology. Annals of Operations Research 181 (1), 515–538. https://doi.org/10.1007/s10479-010-0783-1.

Gładysz, B., 2017. Fuzzy-Probabilistic PERT. Annals of Operations Research 258 (2), 437–452. https://doi.org/10.1007/s10479-016-2315-0.

Goldratt, E.M., 2017. Critical Chain: A Business Novel. Routledge.

Hamouda, A.E.D., 2014. Using Agile story points as an estimation technique in CMMI organizations. In: 2014 Agile Conference, 16–23. Kissimmee, FL, USA: IEEE. https://doi.org/10.1109/AGILE.2014.11.

Inayat, I., Salim, S.S., Marczak, S., Daneva, M., Shamshirband, S., 2015. A systematic literature review on agile requirements engineering practices and challenges. Computers in Human Behavior 51, 915–929. https://doi.org/10.1016/j.chb.2014.10.046.

Islam, M.S., Mohandes, S.R., Mahdiyar, A., Fallahpour, A., Olanipekun, A.O., 2022. A coupled genetic programming Monte Carlo simulation–based model for cost overrun prediction of thermal power plant projects. Journal of Construction Engineering and Management 148 (8), 04022073. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002327.

Kelley, J.E., Walker, M.R., 1959. Critical-path planning and scheduling. In: Papers Presented at the December 1–3, 1959, Eastern Joint IRE-AIEE-ACM Computer Conference on IRE-AIEE-ACM '59 (Eastern), 160–73. Boston, Massachusetts: ACM Press, 1959. https://doi.org/10.1145/1460299.1460318.

Kisielnicki, J., Misiak, A.M., 2017. Effectiveness of Agile compared to Waterfall implementation methods in IT projects: analysis based on business intelligence projects. Foundations of Management 9 (1), 273–286. https://doi.org/10.1515/fman-2017-0021.

Korytkowski, P., Malachowski, B., 2019. Competence-based estimation of activity duration in IT projects. European Journal of Operational Research 275 (2), 708–720. https://doi.org/10.1016/j.ejor.2018.11.061.

Leach, L.P., 1999. Critical chain project management improves project performance. Project Management Journal 30 (2), 39–51. https://doi.org/10.1177/875697289903000207.

Levenberg, K., 1944. A method for the solution of certain non-linear problems in least squares. Quarterly of Applied Mathematics 2 (2), 164–168. https://doi.org/10.1090/qam/10666.

Mahmoodzadeh, A., Nejati, H.R., Mohammadi, M., 2022. Optimized machine learning modelling for predicting the construction cost and duration of tunnelling projects. Automation in Construction 139, 104305. https://doi.org/10.1016/j.autcon.2022.104305.

Miranda, P., Faria, J.P., Correia, F.F., Fares, A., Graça, R., Moreira, J.M., 2021. An analysis of Monte Carlo simulations for forecasting software projects. In: Proceedings of the 36th Annual ACM Symposium on Applied Computing, 1550–58. Virtual Event Republic of Korea: ACM, 2021. https://doi.org/10.1145/3412841.3442030.

Moreira, M.E., 2013. Being Agile: Your Roadmap to Successful Adoption of Agile. Apress.

Morgenshtern, O., Raz, T., Dvir, D., 2007. Factors affecting duration and effort estimation errors in software development projects. Information and Software Technology 49 (8), 827–837. https://doi.org/10.1016/j.infsof.2006.09.006.

Paasivaara, M., Behm, B., Lassenius, C., Hallikainen, M., 2018. Large-scale agile transformation at Ericsson: a case study. Empirical Software Engineering 23 (5), 2550–2596. https://doi.org/10.1007/s10664-017-9555-8.

Список источников

Abouelela, M., Benedicenti, L., 2010. Bayesian network based XP process modelling. International Journal of Software Engineering & Applications 1 (3), 1–15. https://doi.org/10.5121/ijsea.2010.1301.

Acebes, F., Pereda, M., Poza, D., Pajares, J., Galán, J.M., 2015. Stochastic earned value analysis using Monte Carlo simulation and statistical learning techniques. International Journal of Project Management 33 (7), 1597–1609. https://doi.org/10.1016/j.ijproman.2015.06.012.

Aronson, E., Gerard, E., 1966. Beyond Parkinson's Law: the effect of excess time on subsequent performance. Journal of Personality and Social Psychology 3 (3), 336–339. https://doi.org/10.1037/h0023000.

Barrientos-Orellana, A., Ballesteros-Pérez, P., Mora-Melia, D., González-Cruz, M.C., Vanhoucke, M., 2021. Stability and accuracy of deterministic project duration forecasting methods in earned value management. Engineering, Construction and Architectural Management 29 (3). https://doi.org/10.1108/ECAM-12-2020-1045.

Dubois, D., Fargier, H. Fortemps, P., 2003. Fuzzy scheduling: modelling flexible constraints vs. coping with incomplete knowledge. European Journal of Operational Research 147 (2), 231–252. https://doi.org/10.1016/S0377-2217(02)00558-1.

Escandon-Bailon, V., Cervantes, H., García-Nájera, A., Zapotecas-Martínez. S., 2021. Analysis of the multi-objective release plan rescheduling problem. Knowledge-Based Systems 220, 106922. https://doi.org/10.1016/j.knosys.2021.106922.

García, C.B.G., Pérez, J.G., Rambaud, S.C., 2010. Proposal of a new distribution in PERT methodology. Annals of Operations Research 181 (1), 515–538. https://doi.org/10.1007/s10479-010-0783-1.

Gładysz, B., 2017. Fuzzy-Probabilistic PERT. Annals of Operations Research 258 (2), 437–452. https://doi.org/10.1007/s10479-016-2315-0.

Goldratt, E.M., 2017. Critical Chain: A Business Novel. Routledge.

Hamouda, A.E.D., 2014. Using Agile story points as an estimation technique in CMMI organizations. In: 2014 Agile Conference, 16–23. Kissimmee, FL, USA: IEEE. https://doi.org/10.1109/AGILE.2014.11.

Inayat, I., Salim, S.S., Marczak, S., Daneva, M., Shamshirband, S., 2015. A systematic literature review on agile requirements engineering practices and challenges. Computers in Human Behavior 51, 915–929. https://doi.org/10.1016/j.chb.2014.10.046.

Islam, M.S., Mohandes, S.R., Mahdiyar, A., Fallahpour, A., Olanipekun, A.O., 2022. A coupled genetic programming Monte Carlo simulation–based model for cost overrun prediction of thermal power plant projects. Journal of Construction Engineering and Management 148 (8), 04022073. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002327.

Kelley, J.E., Walker, M.R., 1959. Critical-path planning and scheduling. In: Papers Presented at the December 1–3, 1959, Eastern Joint IRE-AIEE-ACM Computer Conference on IRE-AIEE-ACM '59 (Eastern), 160–73. Boston, Massachusetts: ACM Press, 1959. https://doi.org/10.1145/1460299.1460318.

Kisielnicki, J., Misiak, A.M., 2017. Effectiveness of Agile compared to Waterfall implementation methods in IT projects: analysis based on business intelligence projects. Foundations of Management 9 (1), 273–286. https://doi.org/10.1515/fman-2017-0021.

Korytkowski, P., Malachowski, B., 2019. Competence-based estimation of activity duration in IT projects. European Journal of Operational Research 275 (2), 708–720. https://doi.org/10.1016/j.ejor.2018.11.061.

Leach, L.P., 1999. Critical chain project management improves project performance. Project Management Journal 30 (2), 39–51. https://doi.org/10.1177/875697289903000207.

Levenberg, K., 1944. A method for the solution of certain non-linear problems in least squares. Quarterly of Applied Mathematics 2 (2), 164–168. https://doi.org/10.1090/qam/10666.

Mahmoodzadeh, A., Nejati, H.R., Mohammadi, M., 2022. Optimized machine learning modelling for predicting the construction cost and duration of tunnelling projects. Automation in Construction 139, 104305. https://doi.org/10.1016/j.autcon.2022.104305.

Miranda, P., Faria, J.P., Correia, F.F., Fares, A., Graça, R., Moreira, J.M., 2021. An analysis of Monte Carlo simulations for forecasting software projects. In: Proceedings of the 36th Annual ACM Symposium on Applied Computing, 1550–58. Virtual Event Republic of Korea: ACM, 2021. https://doi.org/10.1145/3412841.3442030.

Moreira, M.E., 2013. Being Agile: Your Roadmap to Successful Adoption of Agile. Apress.

Morgenshtern, O., Raz, T., Dvir, D., 2007. Factors affecting duration and effort estimation errors in software development projects. Information and Software Technology 49 (8), 827–837. https://doi.org/10.1016/j.infsof.2006.09.006.

Paasivaara, M., Behm, B., Lassenius, C., Hallikainen, M., 2018. Large-scale agile transformation at Ericsson: a case study. Empirical Software Engineering 23 (5), 2550–2596. https://doi.org/10.1007/s10664-017-9555-8.

The article was submitted 18.09.2024, approved after reviewing 30.09.2024, accepted for publication 08.10.2024.

Статья поступила в редакцию 18.09.2024, одобрена после рецензирования 30.09.2024, принята к публикации 08.10.2024.

About authors:

1. Nikita Denisov, Student at the Institute of Computer Science and Technology, Peter the Great St. Petersburg Polytechnic University, Saint Petersburg, Russian Federation.

2. Aleksei Gintciak, Ph.D in technology, head of Laboratory of Digital modeling of Industrial systems, Peter the Great St. Petersburg Polytechnic University, Saint Petersburg, Russian Federation. https://orcid.org/0000-0002-9703-5079, aleksei.gintciak@spbpu.com

3. Zhanna Burlutskaya, Junior Researcher of Laboratory of Digital modeling of Industrial systems, Peter the Great St. Petersburg Polytechnic University, Saint Petersburg, Russian Federation. https://orcid.org/0000-0002-5680-1937, zhanna.burlutskaya@spbpu.com

4. Darya Fedyaevskaya, Laboratory assistant in Laboratory of Digital modeling of Industrial systems, Peter the Great St. Petersburg Polytechnic University, Saint Petersburg, Russian Federation. https://orcid.org/0000-0002-2993-6473, darya.fedyaevskaya@spbpu.com

5. Salbek Beketov, Analyst in Laboratory of Digital modeling of Industrial systems, Peter the Great St. Petersburg Polytechnic University, Russian Federation. https://orcid.org/0009-0009-6448-9486, salbek.beketov@spbpu.com

Информация об авторах:

1. Никита Денисов, студент института компьютерных наук и технологий, Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Российская Федерация.

2. Алексей Гинцяк, кандидат технических наук, заведующий лабораторией «Цифровое моделирование индустриальных систем», Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Российская Федерация. https://orcid.org/0000-0002-9703-5079, aleksei.gintciak@spbpu.com

3. Жанна Бурлуцкая, младший научный сотрудник лаборатории «Цифровое моделирование индустриальных систем», Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Российская Федерация. https://orcid.org/0000-0002-5680-1937, zhanna.burlutskaya@spbpu.com

4. Дарья Федяевская, лаборант лаборатории «Цифровое моделирование индустриальных систем», Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Российская Федерация. https://orcid.org/0000-0002-2993-6473, darya.fedyaevskaya@spbpu.com

5. Сальбек Бекетов, аналитик лаборатории «Цифровое моделирование индустриальных систем», Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Российская Федерация. https://orcid.org/0009-0009-6448-9486, salbek.beketov@spbpu.com

SECTION 2

ENTERPRISES AND THE SUSTAINABLE DEVELOPMENT OF REGIONS

РАЗДЕЛ 2

ПРЕДПРИЯТИЯ И УСТОЙЧИВОЕ РАЗВИТИЕ РЕГИОНОВ

Research article
DOI: https://doi.org/10.48554/SDEE.2024.3.2

Improving the Information Security of Industrial Enterprises through the Automation of Data and Information Message Transmission Processes

Magomedrasul Buchaev[1], Prokhor Polyakov[2*]

[1]Dagestan State University of National Economy, Dagestan, Russia, buchaev_ma@mail.ru
[2]Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia, prohor@polyakov-box.ru
[*]Corresponding author: prohor@polyakov-box.ru

Abstract

This article focuses on improving the information security of industrial enterprises through the automation of data transmission processes. As a solution, an autonomous unmanned aerial vehicle (UAV) equipped with three microcontrollers is proposed to handle flight control, data processing and transmission and information protection. The system utilises infrared data transmission channels, hardware encryption and a mechanism for the physical destruction of the storage medium, ensuring a high level of protection against cyberattacks and data breaches. The drone's architecture is isolated from corporate networks and features mobility and autonomy, making it effective in environments with limited infrastructure. The modular design of the device allows for adaptation to various application scenarios. The research results demonstrate that the proposed solution provides reliable and secure data transmission, enhancing the resilience of enterprises to modern cyber threats.

Keywords: information security, industrial enterprise, process automation, solution development, unmanned delivery vehicle, electrical device schematic

Citation: Buchaev, M., Polyakov, P., 2024. Improving the Information Security of Industrial Enterprises through the Automation of Data and Information Message Transmission Processes. Sustainable Development and Engineering Economics 3, 2. https://doi.org/10.48554/SDEE.2024.3.2

Научная статья
УДК 347.7
DOI: https://doi.org/10.48554/SDEE.2024.3.2

Повышение Информационной Безопасности Промышленного Предприятия через Автоматизацию Процессов Передачи Данных и Информационных Сообщений

Магомедрасул Бучаев[1], Прохор Поляков[2]

[1]Дагестанский государственный университет народного хозяйства, Дагестан Россия, buchaev_ma@mail.ru
[2]Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Россия, prohor@polyakov-box.ru
[*]Автор, ответственный за переписку: prohor@polyakov-box.ru

Аннотация

Статья посвящена повышению информационной безопасности промышленных предприятий через автоматизацию процессов передачи данных. В качестве решения предложен автономный беспилотный летательный аппарат, оснащённый тремя микроконтроллерами для управления полётом, обработки и передачи данных, а также защиты информации. Система использует инфракрасные каналы передачи данных, аппаратное шифрование и механизм физического уничтожения носителя, что обеспечивает высокий уровень защиты от кибератак и утечек. Архитектура дрона изолирована от корпоративных сетей, обладает мобильностью и автономностью, что делает её эффективной в условиях ограниченной инфраструктуры. Модульная конструкция устройства позволяет адаптировать его под различные сценарии применения. Результаты исследования показывают, что предложенное решение обеспечивает надёжную и безопасную передачу данных, повышая устойчивость предприятий к современным киберугрозам.

Ключевые слова: информационная безопасность, промышленное предприятие, автоматизация процессов, разработка решения, беспилотное средство доставки, электрическая схема устройства

Цитирование: Бучаев, М., Поляков, П., 2024. Повышение Информационной Безопасности Промышленного Предприятия через Автоматизацию Процессов Передачи Данных и Информационных Сообщений. Sustainable Development and Engineering Economics 3, 2. https://doi.org/10.48554/SDEE.2024.3.2

1. Introduction

Modern production processes are increasingly dependent on automated control systems and data transmission (Borzov et al., 2024). Disruptions in this area, such as leaks of confidential information, cyber-attacks or system failures, can lead to serious consequences, including production downtime, financial losses, deterioration of the company's reputation and even a threat to the physical safety of employees and equipment (Starchenkova, 2023). The InfoWatch Expert and Analytical Center reported that among all types of compromised information in the global industry, the share of trade secrets increased from 38.4% to 66.9% in 20231.

In the context of the growing integration of industrial systems with digital technologies and the Internet of Things (IoT), enterprises are facing an increasing number of cyber threats, which require the use of comprehensive measures to protect data, ensure the integrity of production processes and minimise the risks associated with unauthorised access or interference (Rodionov et al., 2023).

The relevance of the topic of this study is determined both by the development of digital technologies in economic relations and by a significant lag—a kind of gap in the regulatory framework for the introduction of modern information technologies into society and the public administration system, especially for language technologies.

The purpose of this article is to develop automation tools for data transmission and information messages using innovative technologies to improve the information security of industrial enterprises. To achieve this goal, it is necessary to solve the following tasks:

1. Analysis of current threats to information security in the industry and identification of the main risks associated with data transmission

2. The study of modern technologies of automated information transmission and their impact on the protection of industrial systems

3. Development of the concept of secure data transmission using autonomous drones

4. Definition of key principles of information security for automated data transmission systems

5. Development of a drone model for the secure transmission of information, taking into account hardware and software specialisation, encryption capabilities and a data destruction mechanism.

The scientific novelty lies in the fact that threats to information security are highlighted, possible directions for development are presented, trends in the use of modern technologies in the field of automation are identified and a solution is presented.

2. Materials and methods

Information security issues in the industry are being actively investigated in light of the growing threats of the digital world (Timerbulatov, 2023). The main trends in automated data transmission are revealed by the developments of ATLAS, KOTMI-14, Rustechnologiya and the Association 'Consortium of Domestic Developers of Data Storage Systems'. These companies are key participants in the creation and implementation of domestic solutions in the field of automated data transmission, which makes a significant contribution to strengthening information security.

Studies such as those of Corallo et al. (2021) and Polyakov and Konnikov (2024) highlight the increasing frequency of cyber-attacks on manufacturing enterprises (Vasiliev, 2023), driven by the increasing integration of digital technologies and IoT (Borzov et al., 2024).

Given that industry is the locomotive of the economy for the state, it is necessary to ensure the timely introduction of innovations2. Automated data transmission systems optimise production process-

[1] Data leaks in Russia. URL: https://d-russia.ru/wp-content/uploads/2024/03/utechki.pdf (date of request: 08/20/2024).
[2] Economics. URL: https://tass.ru/ekonomika/15687539?utm_source (accessed: 08/20/2024)

es, reduce time and financial costs and significantly increase the level of information security, which is crucial for protecting strategically important information (Borremans and Kseshinski, 2023). Let us look at the main trends that are shaping the future of automatic information processing.

Table 1. Trends in automatic information processing (Kelly, 2017; Gugutishvili and Borremans, 2021)

Trend name	Description of the trend
Introduction of 5G networks and the development of Wi-Fi 7	They provide ultra-high data transfer rates and minimal latency, which contributes to more efficient automation of information transfer processes.
Using artificial intelligence (AI) and machine learning	AI and machine learning make it possible to analyse large amounts of data in real time, optimizing transmission processes and ensuring that systems adapt to changing conditions.
Development of Internet of Things (IoT) technologies	The integration of iOS devices into industrial systems allows data to be collected and transmitted automatically, improving monitoring and management of production processes.
Cloud computing and data storage	The use of cloud services provides flexibility and scalability in data storage and processing, which simplifies the automation of information transfer between different systems and devices.
Cybersecurity and blockchain	As the volume of transmitted data increases, the need to protect it increases. Blockchain technologies ensure the transparency and security of data transmission, minimizing the risks of unauthorised access.

Automation of information processing processes plays a strategic role for industrial enterprises engaged in covert operations, ensuring that cyber threats are countered, data leakage risks are minimized, and strict regulatory requirements are met. The most important aspect of developing devices for such purposes is the definition of key principles of data transmission, including autonomy, isolation and resistance to potential risks (Syatraikin, 2023). These characteristics form the core of creating reliable and secure solutions capable of providing a high level of information security and stability in the face of modern challenges. Let us differentiate the highlighted principles among themselves.

Autonomy implies the ability of a device to function independently from external systems and networks. This is critically important for industrial enterprises, as autonomous devices minimise the risks associated with the vulnerability of external networks, including the internet. For example, data transmission can be carried out through closed circuits or internal communication channels, which eliminates the influence of external factors, such as network failures or attacks on infrastructure (Jia and Rodionov, 2022).

Isolation refers to the physical and software separation of a device or data transmission system from the external environment. This principle prevents unauthorised access to information from the outside. To implement it, security technologies are used, such as hardware gateways that block direct communication with external networks or the use of specialised protocols that exclude data transmission in unencrypted form. Isolated systems provide an additional level of security, which is especially important for enterprises working with confidential or strategically important information (Konnikov et al., 2024).

Risk tolerance protects a device from a range of threats, including cyberattacks, hardware failures and human factors. This is achieved using modern encryption technologies, intrusion detection and prevention systems (IDS/IPS), data backup and rapid recovery mechanisms in the case of accidents. In addition, an important element is testing the device for resistance to cyber-attacks, for example, simulating attacks in order to check vulnerabilities and eliminate them at the development stage (Konnikov, 2024).

3. Results

Next, a solution (Figure 1) will be presented, developed by the authors, to enhance the automation of data transmission in an industrial setting. It comprises a description of the rationale for selecting an unmanned aerial vehicle (hereafter referred to as ‘drone’) for this project, as well as an overview of its components designed for the secure transmission and storage of sensitive data.

The selection of a drone for secure information transmission is justified by the following:

1. Physical separation of information flows. The use of a drone eliminates the need to transfer confidential information through corporate networks, which reduces the risks associated with network attacks, data leaks and unauthorised access. The drone functions as an autonomous ‘offline’ data transmission channel that leaves a minimal digital footprint and provides an increased level of security.

2. Minimising the length of the communication channel. Infrared data transmission technology is characterised by the need for direct visibility between the transmitter and receiver as well as a limited range. These features significantly complicate the possibility of unauthorised data interception by third parties. An attempt to direct an infrared transmitter at a moving, unmanned aerial vehicle within the territory of an enterprise is practically impossible without direct physical access to the place of its flight.

3. Flexibility and autonomy. An unmanned aerial vehicle does not depend on an enterprise’s infrastructure, whether it is a cable or wireless network. It is capable of delivering data or performing tasks in remote areas and production sites where there is no wired network or where Wi-Fi deployment is undesirable or difficult.

4. Speed and efficiency. When it is necessary to transfer a significant amount of data quickly between points, for example, in the case of force majeure or failure of the main communication channel, using a drone may be a more efficient and faster solution. This is due to its ability to provide quick setup and autonomy, surpassing in speed and convenience the organisation of a temporary communication network or the physical transportation of data by humans.

5. Multi-level security. On the one hand, the drone guarantees physical protection due to the mobility and controllability of the device, access to which is strictly limited. On the other hand, it is equipped with a built-in data destruction system. In the event of an emergency, such as an attempt to seize, break in or unauthorised opening of a case, all confidential information is immediately destroyed.

Modern technologies and architectural solutions are employed in unmanned aerial vehicles to ensure the reliability, safety and high efficiency of data transmission. In this regard, let us consider the key aspects that contribute to the innovation and functional stability of these devices in various application contexts.

1. Specialisation of hardware and software. Three separate microcontrollers or three cores with distinct functions are required to concurrently perform critical operations – flight control, which requires deterministic real-time processing; encryption/decryption and data transmission, which necessitate high-speed execution of cryptographic algorithms and secure communication; and a protection and destruction system, which must promptly and independently respond to emergency situations.

2. Despite the apparent obsolescence of infrared data transmission technology, there are several significant advantages to using it. A narrow focus on the infrared beam significantly reduces the risk of unauthorised data interception and provides increased protection. The lack of radio frequency radiation eliminates the possibility of intercepting data over long distances typical of radio channels. Additionally, the technology has a high degree of ease of implementation and efficiency over short distances, making it suitable for use in workshops or offices.

3. Hardware encryption. The ESP32 microcontroller or external cryptoprocessor can be used to unload some of the processing load from the main microcontroller, allowing for faster encryption/decryption operations when working with encrypted files stored on an SD card. This separation of duties ensures higher throughput.

4. Physical destruction of media. Unlike logical or cryptographic deletion, mechanical destruction ensures the irrecoverability of data, even through direct reading of the storage medium.

5. Scalability and upgradability. The architecture, based on modular components and standard interfaces, simplifies the process of replacing or upgrading individual components (e.g., installing a faster SD module, replacing an IR module with an improved one, etc.).

Figure 1 illustrates the structural organisation of a data management system utilizing infrared transmitters and ESP8266 modules. This system demonstrates the potential for integrating wireless technologies and localised data transmission channels, enabling a secure and self-sufficient network with minimal reliance on external infrastructure.

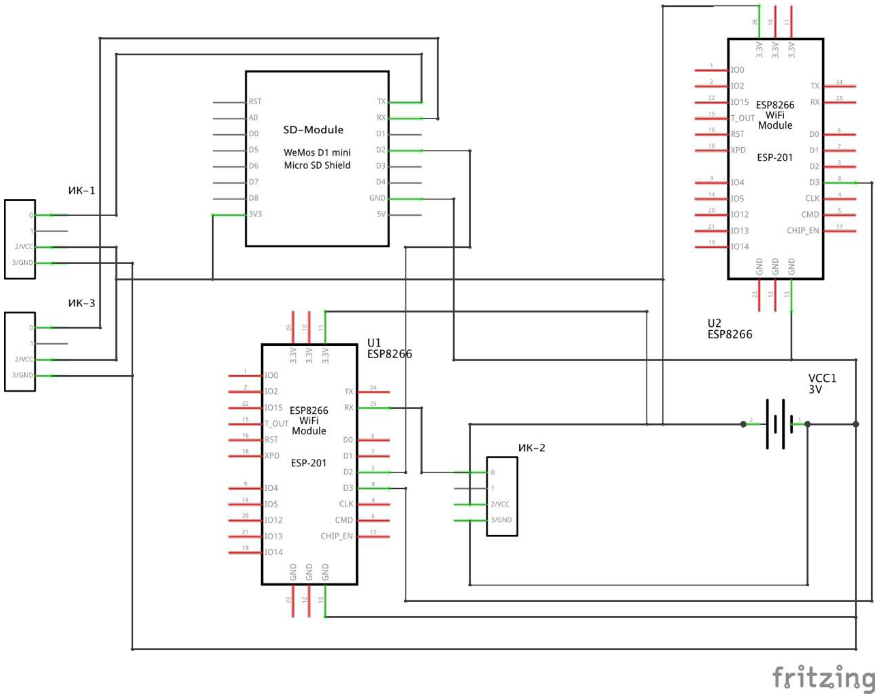

Figure 1. An electrical circuit reflecting mainly the device of the information receiving/transmitting unit

1. General Architecture and Purpose of Subsystems

1.1 Flight Subsystem:

The primary flight microcontroller (MC) is the heart of the flight system, ensuring stable flight and control. The drone requires a high-performance microcontroller with hardware support for sensors (gyroscopes, accelerometers, barometers, etc.) for stable operation. Examples include the STM32F4 line (based on the ARM Cortex-M4 architecture) or specialised boards based on PX4 or Ardupilot, such as the Matek F405.

These microcontrollers provide precise motor control through built-in timers and peripheral devices (PWM channels) and have sufficient RAM for stabilization filters, such as Kalman filters or complementary filters. They are also compatible with sensors through the I2C, SPI or UART bus.

Electronic motor control system (ESC) and brushless electric motors: Brushless motors are known for their high efficiency and light weight, which are critical factors when designing a compact drone. ESCs convert the pulse width modulation (PWM) signal from the controller into suitable control pulses for the motor and monitor the current and voltage across the windings.

Optional GPS/GLONASS system: To ensure more accurate positioning and the ability to navigate according to pre-defined coordinates, the system may include a GPS/GLONASS receiver, especially for projects that involve longer flights or operations beyond the operator's line of sight.

Data reception/transmission subsystem:

- Microcontroller for communication and data storage:

Figure 1 shows the ESP8266 (ESP-201) microcontroller or a similar module (such as the WeMos D1 mini), which serves as the communication and data storage hub. This microcontroller takes the following actions:

1. Writes and reads data to an SD card through the SPI interface (a SD module based on the WeMos D1 Mini Micro SD Shield has been specified)

2. Work with infrared (IR) ports, which are used for 'spot' data transmission over short distances with a limited field of view

3. The logic of encryption/decryption (or the preparation of data for transmission if cryptography is implemented in conjunction with another module)

- SD (secure digital) module

Data (technological or commercial information) is stored in non-volatile memory before being sent, which is convenient for temporary buffering or in situations where communication may be interrupted. The SD card provides a fairly large amount of memory with small dimensions and minimal power consumption.

- IR (infrared) modules

Figure 1 shows three IR ports – IR-1, IR-2, and IR-3 – each of which has a specific function:

1. IR-1 is used only for data transmission (TX). It is used to transmit information from the SD card to the destination.

2. IR-3 is used only for data reception (RX). This is used to write new data to the SD card (e.g., when receiving assignments or new encryption keys).

3. IR-2 is used for the transmission (TX) of encrypted flight coordinates to ESP32 (or other on-board controllers).

This separate configuration (two ports for receiving and one for transmitting, or vice versa) avoids errors in determining the direction of data flow, simplifies management and increases security (each channel is strictly 'tuned' for input or output).

- Encryption

ESP32 can decrypt flight coordinates and send them to another "flight" microcontroller. The use of ESP32 (with hardware cryptography acceleration) is justified by the need for fast encryption/decryption of data without a significant load on the primary flight MCU.

1.3 Data destruction system

- A separate microcontroller or dedicated high-priority unit within an existing MC to monitor for deviations from the intended course and possible signs of external interference (sudden fluctuations or loss of communication with the flight control system). This unit would be responsible for making the decision to physically destroy the data if necessary. Due to the high criticality of data erasure or destruction, it is necessary to implement a separate control loop to minimise delays and prevent conflicts with other processes or resources.

- In the event of a potential threat being detected by the microcontroller, the pyropatron located in close proximity to the SD card will be activated, physically destroying the card. This method virtually eliminates the possibility of recovering data, providing a much higher level of security compared to logical methods of information deletion.

Sensors for failure or deviation from the course

The drone compares the planned route in real time with the actual navigational data (GPS/gyroscope/accelerometer) and, if there is a substantial deviation, the system concludes that there has been unauthorised interference, which triggers a process of data destruction.

4. Conclusion

The drone developed in this research for secure data transmission integrates advanced hardware and software solutions. Its design is based on three separate microcontrollers that fulfill critical functions – flight management, data processing and storage, as well as information protection with the capability of its destruction. This method enables high reliability, independence and security while transferring confidential data under various circumstances.

The initial system is accountable for flight management and implements autopilot features. The microcontroller within this system monitors the motors, transmits commands to speed controllers (ESCs) and processes the path based on coordinates provided by the second microcontroller.

The second system focuses on data processing and transfer. It comprises an SD module for storing and retrieving information as well as three infrared (IR) ports. The IR-1 port is designed to transmit data from the SD card to a designated location, the IR-3 port is used to record data onto the SD card and the IR-2 port transmits encrypted flight data to the control system.

The third system ensures data integrity. If the drone veers off course or is captured, a self-destruct mechanism is activated that physically destroys the SD card. This prevents data recovery, even with specialised tools. This solution provides maximum security and ensures that sensitive information is not leaked in the event of a device compromise.

The drone offers several significant advantages that make it an optimal solution for secure data transfer tasks. The physical separation of communication channels prevents interference between systems, while isolation from corporate networks reduces the risk of cyberattacks. IR modules ensure accurate and directed data transmission, making interception difficult. The flexibility of the device allows for effective use in situations in which stationary infrastructure may not be available or desirable.

Due to its modular design, the drone facilitates the upgrading of individual components. For instance, the SD (storage) module can be replaced with a faster model, or the IR modules can be enhanced to increase the range and reliability of transmission. This versatility makes the device suitable for various applications, including corporate, scientific and industrial settings.

References

Borremans, A., Kseshinski, E., 2023. Graph theory and set theory as instruments for e-commerce. Fundamental and applied research in the field of management, economics and trade, in: Proceedings of the All-Russian Scientific, Practical and Educational Conference, Polytechnic Press, St. Petersburg 3, pp. 248–257.

Borzov, A., Mitrofanova, V., Starchenkova, O., 2024. Development of a strategy for the development of the aviation industry in the Russian Federation. Bulletin of the Academy of Knowledge 3(62), 79–88.

Corallo, A., Lazoi, M., Lezzi, M., Pontrandolfo, P. 2021. Cybersecurity challenges for manufacturing systems 4.0: Assessment of the business impact level. IEEE Transactions on Engineering Managements 1–21. doi:10.1109/tem.2021.3084687

Gugutishvili, D., Borremans, A., 2021. Analysis of the digital maturity of industries and states. Fundamental and applied research in the field of management, economics and trade, in: Proceedings of the All-Russian Scientific, Practical and Educational Conference, Polytechnic Press. Saint Petersburg, 1, pp. 39–43.

Jia, Ts., Rodionov, D., 2022. The use of digital twins for industrial development. In Digital Transformation of Economic Systems: Problems and Prospects (ECOPROM-2022), pp. 159–162.

Kelly, K. 2017. Inevitable: 12 Technological Trends that Define Our Future. Mann, Ivanov and Ferber.

Konnikov, E., 2024. Modeling of the properties of an enterprise as a subject of the information environment in the context of the development of regional spatially localized subsystems. The economy of the North-West: Problems and Prospects of Development 3(78), 151–157.

Konnikov, E., Rodionov, D., Kryzhko, D., 2024. Interpretation of the results of modeling the effect of an information pulse in a digital environment. Natural Sciences and Humanities Studies 5 (55), 188–193.

Polyakov, P., Konnikov, E., 2024. The strategy of digital transformation of the economy in the Russian Federation. The mechanism of imple-

mentation of the strategy of socio-economic development of the state, in: Proceedings of the XVI International Scientific and Practical Conference, Makhachkala, September 25–26, 2024, pp. 358–361.
Rodionov, D., Eremina, I., Wallask, V., 2023. Prospects for the development of small innovative entrepreneurship in the context of spatial resource allocation. Natural Sciences and Humanities Research 6(50), 407–414.
Starchenkova, O., 2023. Comparative analysis of business process automation systems. Economic Sciences 221, 346–352.
Syatraikin, E., 2023. Basic principles of data transmission capacities in wireless networks. Formation of a Competitive Environment, Competitiveness and Strategic Management of Enterprises, Organizations and Regions, 516.
Timerbulatov, T., 2023. The State policy of the Russian Federation in the field of information security: Historical experience and implementation: 1991 – 2021 (Dissertation for the degree of Candidate of Historical Sciences, 5.6.1). Peoples' Friendship University of Russia.
Vasiliev, A., 2023. The reasons for the increase in the number of cyber attacks: Analysis of technical and non-technical factors. Systems Analysis and Applied Computer Science (3), 48–54.

Список источников

Борзов, А., Митрофанова, В., Старченкова, О., 2024. Разработка стратегии развития отраслей авиационной промышленности Российской Федерации. Вестник Академии знаний, 3(62), 79-88.
Васильев, А., 2023. Причины роста количества кибератак: анализ технических и нетехнических факторов. Системный анализ и прикладная информатика, (3), 48-54.
Гугутишвили, Д., Борреманс, А., 2021. Анализ цифровой зрелости отраслей и государств. Фундаментальные и прикладные исследования в области управления, экономики и торговли : Сборник трудов Всероссийской научно-практической и учебно-методической конференции: ПОЛИТЕХ-ПРЕСС. Санкт-Петербург, 1, 39-43.
Келли, К. 2017. Неизбежно: 12 технологических трендов, которые определяют наше будущее. Манн, Иванов и Фербер.
Конников, Е., 2024. Моделирование свойств предприятия как субъекта информационной среды в контексте развития региональных пространственно-локализованных подсистем. Экономика Северо-Запада: проблемы и перспективы развития, 3(78), 151-157.
Конников, Е., Родионов, Д., Крыжко, Д., 2024. Интерпретация результатов моделирования эффекта информационного импульса в цифровой среде. Естественно-гуманитарные исследования, (5 (55)), 188-193.
Поляков, П., & Конников, Е., 2024. Стратегия цифровой трансформации экономики в Российской Федерации. В Механизм реализации стратегии социально-экономического развития государства: Сборник материалов XVI Международной научно-практической конференции, Махачкала, 25–26 сентября 2024 года. 358-361.
Родионов, Д., Еремина, И., Валласк, В., 2023. Перспективы развития малого инновационного предпринимательства в условиях пространственного распределения ресурсов. Естественно-гуманитарные исследования, 6(50), 407-414.
Старченкова, О., 2023. Сравнительный анализ систем автоматизации бизнес-процессов. Экономические науки, 221, 346-352.
Сятрайкин, Е., 2023. Основные принципы мощностей передачи данных в беспроводных сетях. Формирование конкурентной среды, конкурентоспособность и стратегическое управление предприятиями, организациями и регионами, с. 516.
Тимербулатов, Т., 2023. Государственная политика Российской Федерации в сфере информационной безопасности : исторический опыт и реализация : 1991–2021 гг. (Диссертация на соискание ученой степени кандидата исторических наук, 5.6.1). Российский университет дружбы народов.
Утечки данных в России. URL: https://d-russia.ru/wp-content/uploads/2024/03/utechki.pdf (дата обращения: 20.08.2024).
Цзя, Ц., Родионов, Д., 2022. Применение цифровых двойников для развития промышленности. In Цифровая трансформация экономических систем: проблемы и перспективы (ЭКОПРОМ-2022). 159-162.
Экономика. URL: https://tass.ru/ekonomika/15687539?utm_source (дата обращения: 20.08.2024)
Borremans, A., Kseshinski, E., 2023. Graph theory and set theory as instruments for e-commerce. В Фундаментальные и прикладные исследования в области управления, экономики и торговли : сборник трудов Всероссийской научно-практической и учебно-методической конференции: Политех-Пресс, Санкт-Петербург, 3, 248-257.
Corallo, A., Lazoi, M., Lezzi, M., Pontrandolfo, P. 2021. Cybersecurity Challenges for Manufacturing Systems 4.0: Assessment of the Business Impact Level. IEEE Transactions on Engineering Management, 1–21. doi:10.1109/tem.2021.3084687

The article was submitted 20.09.2024, approved after reviewing 05.10.2024, accepted for publication 12.10.2024.

Статья поступила в редакцию 20.09.2024, одобрена после рецензирования 05.10.2024, принята к публикации 12.10.2024.

About authors:

1. Magomedrasul Buchaev, postgraduate student, Dagestan State University of National Economy, Dagestan, Russian Federation. buchaev_ma@mail.ru

2. Prokhor Polyakov, laboratory assistant at the Higher School of Engineering and Economics, Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russian Federation. prohor@polyakov-box.ru

Информация об авторах:

1. Магомедрасул Бучаев, аспирант, Дагестанский государственный университет народного хозяйства, Дагестан, Российская Федерация. buchaev_ma@mail.ru

2. Прохор Поляков, лаборант Высшей инженерно-экономической школы, Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Российская Федерация. prohor@polyakov-box.ru

SECTION 3

SUSTAINABLE DEVELOPMENT OF REGIONAL INFRASTRUCTURE

РАЗДЕЛ 3

УСТОЙЧИВОЕ РАЗВИТИЕ РЕГИОНАЛЬНОЙ ИНФРАСТРУКТУРЫ

Research article

DOI: https://doi.org/10.48554/SDEE.2024.3.3

Multidimensional Specification of the Role of Regions in the National Economy Based on Entropy Analysis

Elena Velichko[1], Prokhor Polyakov[2*]

[1]Baltic State Technical University "Voenmekh" named after. D. F. Ustinova, St. Petersburg, Russia, velichko_ed@voenmeh.ru
[2]Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia, prohor@polyakov-box.ru
[*]Corresponding author: prohor@polyakov-box.ru

Abstract

This article considers entropy analysis as a tool for assessing the sustainability and integration of regional economies into national and international economic systems. Three key types of entropy are defined – economic diversification, income and employment distribution and interregional ties. The methodology for calculating entropy indicators based on the generalised Shannon entropy formula is presented. A comparative analysis of three hypothetical regions was conducted on the basis of entropy indices. The obtained results allow us to quantitatively assess the specifics of regional development, identify imbalances and propose strategies to improve the sustainability and economic diversification of regions.

Keywords: regional economy, entropy analysis, diversification, sustainability, integration, economic entropy, income distribution, employment, interregional ties

Citation: Velichko, E., Polyakov, P., 2024. Multidimensional Specification of the Role of Regions in the National Economy Based on Entropy Analysis. Sustainable Development and Engineering Economics 3, 3. https://doi.org/10.48554/SDEE.2024.3.3

Научная статья
УДК 005.6
DOI: https://doi.org/10.48554/SDEE.2024.3.3

Метод Многомерной Спецификации Роли Регионов в Национальной Экономике на Основе Энтропийного Анализа

Елена Величко[1], Прохор Поляков[2]

[1]Балтийский государственный технический университет «Военмех» им. Д. Ф. Устинова, Санкт-Петербург, Россия, velichko_ed@voenmeh.ru
[2]Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Россия, prohor@polyakov-box.ru
[*]Автор, ответственный за переписку: prohor@polyakov-box.ru

Аннотация

В данной статье рассматривается метод энтропийного анализа как инструмент оценки устойчивости и интеграции региональных экономик в национальную и международную экономическую систему. Определены три ключевых типа энтропии: энтропия диверсификации экономики, энтропия распределения доходов и занятости, а также энтропия межрегиональных связей. Представлена методология расчета энтропийных показателей на основе обобщенной формулы энтропии Шеннона. Проведен сравнительный анализ трех гипотетических регионов на основе энтропийных индексов. Полученные результаты позволяют количественно оценить специфику регионального развития, выявить дисбалансы и предложить стратегии повышения устойчивости и экономической диверсификации регионов.

Ключевые слова: региональная экономика, энтропийный анализ, диверсификация, устойчивость, интеграция, экономическая энтропия, распределение доходов, занятость, межрегиональные связи.

Цитирование: Величко, Е., Поляков, П., 2024. Метод Многомерной Спецификации Роли Регионов в Национальной Экономике на Основе Энтропийного Анализа. Sustainable Development and Engineering Economics 3, 3. https://doi.org/10.48554/SDEE.2024.3.3

1. Introduction

Analysing the role of regions in the national economy is one of the key tasks of the regional economy. The issues of diversification of economic structures, equitable income distribution and integration of regions into interregional and international economic relations require an integrated approach (Zaborovskaya and Starchenkova, 2023). In the context of the growing complexity of economic processes, the use of methods that make it possible to assess multidimensional relationships in economic systems is becoming particularly relevant (Rodionov et al., 2022).

One such approach is to use entropy, which is a quantitative measure of uncertainty and distribution (Pogrebova et al., 2017). The use of entropy indicators not only allows us to assess the degree of diversity and balance of regional economies but also to identify key structural dependencies that determine the sustainability of their development (Arbatskaya et al., 2024.).

Entropy, as a concept borrowed from information theory, is versatile and has the ability to quantify the distribution of elements in a system (Marshalov et al., 2023). In the context of the regional economy, entropy provides a tool for analysing the distribution of economic, social and institutional resources, which allows the following (Rodionov et al., 2024):

1. Assessing the diversification of economic structures

2. Identifying the levels of social justice and employment

3. Analysing the degree of involvement of the region in inter-regional relations

Three key aspects of the regional economy can be expressed through the corresponding types of entropies – economic diversification, income and employment distribution and interregional relations.

2. Materials and methods

The following are the types of entropies and their justifications and significances (Rodionov et al., 2024):

1. Entropy of economic diversification (Titkova, 2017): This indicator measures the distribution of value added or the shares of various industries in the structure of the gross regional product (GRP).

Justification: High entropy indicates a diversified economy that is resistant to external shocks, while low entropy indicates the dominance of one industry, which makes the region vulnerable to fluctuations in demand and prices.

Significance: The entropy of diversification characterises the stability of a region and its ability to adapt to changes in national and global economies.

2. Entropy of income and employment distribution (Veselovsky, 2017): This indicator reflects the distribution of income between different groups of the population or the distribution of employment between industries.

Justification: A high level of entropy indicates a balanced and uniform distribution, contributing to social stability, while a low level of entropy indicates a concentration of wealth or employment in certain groups, which can lead to social tension.

Significance: Socio-economic justice plays a key role in ensuring the sustainable development of the region and preventing internal conflicts.

3. Entropy of inter-regional relations (Ivanov, 2011). This metric estimates the distribution of flows of goods, services, capital and migration between regions.

Justification: High entropy indicates the uniform integration of the region into the national economy, which reduces dependence on individual partners, while low entropy indicates the concentration of flows, making the region dependent on a limited number of connections.

Significance: The region's integration into national and international economic networks directly affects its competitiveness and resilience to external challenges.

The relationship between the types of entropy, the entropy of economic diversification, income and employment distribution and interregional ties are interrelated and form a comprehensive perspective of the region's role in the national economy.

The impact of diversification on social justice: A more diversified economy (high) creates more jobs in different industries, which contributes to an even distribution of employment and income (high).

Connection with inter-regional ties: Diversified and socially balanced regions usually have more stable and multifaceted ties with other regions (high) (Shvets, 2013).

The inverse relationship: The weak integration of the region into the national economy (low) may limit economic diversification, exacerbating social imbalances.

The use of entropy as the basis of multidimensional analysis makes it possible to integrate various aspects of the economic, social and institutional structure of the region into a single conceptual framework (Tyrsin, 2016). This creates opportunities for an objective analysis of the region's role in the national economy and the development of effective strategies for its development (Bozhko, 2012).

3. Results

To quantify the role of a region in the national economy, three types of entropy indicators are used – the entropy of economic diversification (H_{econ}), the entropy of income and employment distribution (H_{soc}) and the entropy of interregional relations (H_{int}). Each of these indicators is based on the generalised Shannon entropy formula (Dulesov et al., 2010):

$$H = -\sum_{i=1}^{n} p_i \log p_i \tag{1}$$

where p_i is the probability (or relative proportion) of the corresponding element in the total population. In this context, this value may represent the share of the industry in the gross regional product (GRP), the share of income of a population group in the total income of the region, the share of labour resources distributed by sector or the share of inter-regional trade attributable to a particular partner.

The entropy of economic diversification (H_{econ}) reflects the degree of uniformity of the distribution of added value between different sectors of the region's economy. If a region is characterised by high specialisation in one or more industries, the value of entropy will be low, while an even distribution of added value among all industries will lead to a maximum value of entropy. Formally, the share of sector I in GRP is determined by the following ratio (Kravchenko, 2015):

$$p_i = \frac{V_i}{\sum_{i=1}^{n} V_i} \tag{2}$$

where V_i is the added value of sector i. Then, the entropy of economic diversification is calculated using the formula:

$$H_{econ} = -\sum_{i=1}^{n} p_i \log p_i \tag{3}$$

At the same time, if $H_{econ} \to 0$, the economy of the region is based on a single industry, which makes it vulnerable to shocks in that sector. However, if $H_{econ} \to \log n$, the region's economy is maximally diversified, which indicates its high stability (Iogman, 2008).

To assess the level of economic concentration, the Herfindahl–Hirschman index (HHI) can be used, which is related to entropy as follows:

$$HHI = \sum_{i=1}^{n} p_i^2 \quad (4)$$

It has a connection with entropy through the following expression:

$$H_{econ} = -\sum_{i=1}^{n} p_i \log p_i = \log n - \frac{HHI}{n} \quad (5)$$

The entropy of income is determined by the distribution of income among m population groups:

$$p_j = \frac{D_j}{\sum_{j=1}^{m} D_j} \quad (6)$$

where D_j is the total income earned by population group j. Then, the entropy of income is determined as follows:

$$H_{soc}^{(inc)} = -\sum_{j=1}^{m} p_j \log p_j \quad (7)$$

For an additional assessment of income concentration, the Gini coefficient GG can be used, which is related to entropy as follows:

$$G = 1 - e^{-H_{soc}^{(inc)}} \quad (8)$$

Likewise, the Theil index, T, which is employed to quantify inequality, can be expressed in terms of entropy according to the following formula:

$$T = \sum_{j=1}^{m} p_j \left(\frac{\log p_j}{\log m}\right) \quad (9)$$

The entropy of employment is calculated in a similar way but taking into account the distribution of labour by economic sector. The proportion of workers employed in sector k is defined as follows:

$$p_k = \frac{E_k}{\sum_{k=1}^{k} E_k} \quad (10)$$

where E_k is the number of employees in the k sector. Then, the entropy of the employment distribution has the following form:

$$H_{soc}^{(emp)} = -\sum_{k=1}^{k} p_k \log p_k \quad (11)$$

Furthermore, the employment concentration index, C_E, can be calculated, thereby revealing the departure from a uniform distribution.

$$C_E = \sum_{k=1}^{k} \left| p_k - \frac{1}{k} \right| \tag{12}$$

The final index of social entropy is as follows:

$$H_{soc} = \frac{H_{soc}^{(inc)} + H_{soc}^{(emp)}}{2} \tag{13}$$

High value H_{soc} indicates an even distribution of income and employment among the population, contributing to social stability, while a low value indicates significant imbalances, which can lead to socio-economic polarisation (Sedykh et al., 2015).

The entropy of inter-regional relations (H_{int}) serves as a measure of the level of integration of a region into both interregional and global economic networks. This entails an analysis of the distribution of goods, investments and migratory flows entering and leaving the region. The proportion of a particular flow in the overall volume of interregional relations is calculated using the following specific formula:

$$p_k = \frac{F_k}{\sum_{k=1}^{p} F_k} \tag{14}$$

where F_k is the volume of a specific flow (exports, imports, investments, migration). The entropy of inter-regional relations is expressed by the following equation:

$$H_{\text{int}} = -\sum_{k=1}^{p} p_k \log p_k \tag{15}$$

The Herfindahl–Hirschman concentration index can be used to assess the concentration of inter-regional links:

$$HHI_{int} = \sum_{k=1}^{p} p_k^2 \tag{16}$$

and the region's specialisation coefficient:

$$S = \frac{1}{\sum_{k=1}^{p} p_k^2} - 1 \tag{17}$$

A composite entropy index is introduced for an integral assessment of the region's role in the national economy:

$$H_{total} = \alpha H_{econ} + \beta H_{soc} + \gamma H_{\text{int}} \tag{18}$$

where the weighting factors are determined based on the specific objectives of the analysis as well as the significance of various aspects of regional development.

Moreover, normalized entropy can be employed for the purposes of comparative analysis (Babichev et al., 2014):

$$H_{norm} = \frac{H_{total}}{\log N} \tag{19}$$

where N is the total number of analysed regions.

Thus, the use of entropy indicators makes it possible to formalise and quantify the specifics of regional development, identifying both its strengths and weaknesses (Kiku, 2005). This approach can serve as a basis for developing strategies for economic diversification, increasing social sustainability and strengthening regional integration into the national economic system (Pashinina et al., 2023).

Three hypothetical regions, namely A, B and C, are posited hereby, for which entropic metrics was determined in accordance with the undermentioned dimensions:

1. The entropy of economic diversification (H_{econ}) measured the uniformity of the distribution of added value across sectors.

2, The entropy of income and employment distribution (H_{soc}) characterised the socio-economic structure.

3. The entropy of interregional relations (H_{int}) evaluated the region's involvement in the national and international economy.

4. The final entropy index (H_{total}) was an aggregated estimate that took into account all three indicators.

The table below shows the calculated values of entropy indicators for each region.

Table 1. Values of entropy indicators for regions

Region	H_{econ}	H_{soc}	H_{int}	H_{total}
Region A	1.544	1.211	1.030	1.308
Region B	1.359	1.002	0.639	1.072
Region C	1.609	1.386	1.099	1.418

Following is an analysis of the results:

1. Economic diversification (H_{econ})

Region C had the highest index (1.609), indicating the most balanced structure of the economy.

Region B showed the lowest value (1.359), indicating relatively diversified specialisation.

Region A (1.544) occupied an intermediate position.

2. Social structure (H_{soc})

Region C had the highest social entropy (1.386), indicating an even distribution of income and employment.

Region B had the lowest value (1.002), indicating a high concentration of income and employment in certain sectors.

Region A was located between them (1.211).

3. Integration into the national economy (H_{int})

Region C also demonstrated the greatest involvement in inter-regional relations (1.099).

Region B had the lowest index (0.639), indicating a high dependence on a limited number of foreign economic partners.

Region A occupied the middle position (1.030).

4. Final index (H_{total})

Region C showed the highest final entropy index (1.418), indicating high stability and balance.

Region B had the lowest value (1.072), indicating weak diversification, low social balance and limited integration.

Region A was located between them (1.308).

4. Conclusion

Region C could be characterised as the most harmonious and stable region, featuring a high degree of economic diversity, equitable income distribution and robust integration into the national economic system.

In contrast, Region A exhibited a relatively high degree of diversification but a less balanced social fabric and an average level of integration.

Region B, on the other hand, demonstrated a significant degree of economic concentration, pronounced social disparities and limited integration into national networks, making it the least resilient among the analysed regions.

Through the application of entropy analysis, we could delineate the salient features of regional progress and propose strategies for its enhancement.

The entropy analysis methodology offers a rigorous and comprehensive approach to evaluating the resilience of regional economic systems. By employing entropy indicators, it becomes possible to formalise and quantify crucial aspects of regional progress, encompassing economic diversification, social equity and the extent of integration into national and global economic frameworks.

A comparative analysis of three hypothetical regions revealed that those with higher entropy exhibited greater stability, reduced reliance on specific industries or partners and a more equitable social fabric. The implementation of this method in practical scenarios allows for the identification of vulnerable regions, anticipation of potential risks and formulation of targeted economic growth strategies.

In future, entropy analysis can expand to encompass additional dimensions, such as technological advancement and environmental sustainability, further enhancing its utility in guiding regional economic development.

References

Arbatskaya, D., Rodionov, D., Ungvari, L., Konnikov, E., 2024. Comparative analysis of approaches to modeling changes in the financial markets of the technological sector of the economy. Soft Measurements and Calculations 74 (1–1), 71–82.

Babichev, S., Tkachev, A., Tkacheva, I., 2014. Model of a system for assessing the quality of DNA microarray data normalization based on the entropy criterion. Intellectual Systems for Decision Making and Problems of Computational Intelligence, 196.

Bozhko, Yu., 2012. Strengthening the role of the region in the socio-economic development of the national economy as a vector for improving regional policy. Socio-economic Phenomena and Processes (10), 29–33.

Dulesov, A., Shvets, S., Khrustalev, V., 2010. Application of Shannon's formula and geometric generalization to determine entropy. Perspectives of Science (3), 92–95.

Iogman, L., 2008. A strategy for diversifying the region's economy. Economic and Social Changes: Facts, Trends, Forecast (1), 78–91.

Ivanov, D., 2011. Methodological aspects of spatial development of foreign economic relations of regions. Problems of Modern Economics (3), 272–274.

Kiku, P., 2005. Information and analytical modeling of medical and ecological processes of public health. Bulletin of the St. Petersburg State Medical Academy named after I. Mechnikova 6(1), 36–43.

Kravchenko, N., 2015. Assessment of the diversification of the regional economy (using the example of the subjects of the Siberian Federal District). Region: Economics and Sociology (4), 65–89.

Marshalov, D., Rodionov, D., Konnikov, E. et al., 2023. Comparative analysis of the effectiveness of approaches to forecasting the share price of a banking sector company. Soft Measurements and Calculations 73 (12–1), 7–15.

Pashinina, P., Rodionov, D., Veselov, A. et al., 2023. Indicative and meaningful analysis of the category of the regional population's need for infrastructure 226, 117–133.

Pogrebova, O., Konnikov, E., Yuldasheva, O., 2017. A fuzzy-multiple model for evaluating a company's sustainable marketing development index, in: International Conference on Soft Computing and Measurements. Federal State Autonomous Educational Institution of Higher Education St. Petersburg State Electrotechnical University named after VI Ulyanova (Lenin) 2, 522–525

Rodionov, D., Konnikov, E., Konnikova, O. et al., 2024. The influence of socio-economic factors on the penetration of internet marketing in various countries. Soft Measurements and Calculations 74(1–1), 48–61.

Rodionov, D., Konnikov, E., Pashinina, P., Shanygin, S., 2024. Thematic modeling of the information environment of media companies: The LDA-TF-IDF toolkit. Soft Measurements and Calculations 76(3), 72–84.
Rodionov, D., Pashinina, P., Konnikov, E., 2022. Quantifiers of the financial market information environment. Economic Sciences 211, 125–128.
Sedykh, N., Korposh, E., Goncharova, E., 2015. The reasons for the socio-economic polarization of Russian regions. Economics and Modern Management: Theory and Practice 10-11-2(53), 136–140.
Shvets, I., 2013. Minimization of entropy in the management of innovative development of the socio-economic system. Economic Policy: Towards a New Paradigm (pp. 110–116).
Titkova, I., 2017. The Herfindahl index and the entropy index as indicators of economic diversification. World Experience and the Economy of Russia's Regions, 375–377.
Tyrsin, A., 2016. Entropy Modeling of Multidimensional Stochastic Systems.
Veselovsky, S., 2017. Globalization and the problem of income inequality in the modern world. Globalization and the Problem of Income Inequality in the Modern World, 1–185.
Zaborovskaya, O., Starchenkova, O., 2023. Development of the region's innovation potential resources as the main objective of regional innovation policy. Bulletin of the Academy of Knowledge 3(56), 97.

Список источников

Арбатская, Д., Родионов, Д., Унгвари, Л., Конников, Е., 2024. Сравнительный анализ подходов к моделированию изменений на финансовых рынках технологического сектора экономики. Мягкие измерения и вычисления, 74 (1-1), pp. 71-82.
Бабичев, С., Ткачев, А., Ткачева, И., 2014. Модель системы оценки качества нормировки данных микромассива ДНК на основе критерия энтропии. Intellectual systems for decision making and problems of computational intelligence, p.196.
Божко, Ю., 2012. Усиление роли региона в социально-экономическом развитии национальной экономики как вектор совершенствования региональной политики. Социально-экономические явления и процессы, (10), pp. 29-33.
Веселовский, С., 2017. Глобализация и проблема неравенства доходов в современном мире. Глобализация и проблема неравенства доходов в современном мире, (2017), pp.1-185.
Дулесов, А., Швец, С. and Хрусталёв, В., 2010. Применение формулы Шеннона и геометрического обобщения для определения энтропии. Перспективы науки, (3), pp.92-95.
Заборовская, О., Старченкова, О., 2023. Развитие ресурсов инновационного потенциала региона как основная задача региональной инновационной политики. Вестник Академии знаний, (3 (56)), с. 97.
Иванов, Д., 2011. Методические аспекты пространственного развития внешнеэкономических связей регионов. Проблемы современной экономики, (3), pp.272-274.
Иогман, Л., 2008. Стратегия диверсификации экономики региона. Экономические и социальные перемены: факты, тенденции, прогноз, (1), стр.78-91.
Кику, П., 2005. Информационно-аналитическое моделирование медико-экологических процессов здоровья населения. Вестник Санкт-Петербургской государственной медицинской академии им. ИИ Мечникова, 6(1), стр. 36-43.
Кравченко, Н., 2015. Оценки диверсификации региональной экономики (на примере субъектов Сибирского федерального округа). Регион: экономика и социология, (4), стр. 65-89.
Маршалов, Д., Родионов, Д., Конников, Е. [и др.], 2023. Сравнительный анализ эффективности подходов к прогнозированию стоимости акций компании банковского сектора. Мягкие измерения и вычисления, 73 (12-1), стр. 7-15.
Пашинина, П., Родионов, Д., Веселов, А. [и др.], 2023. Индикативно-содержательный анализ категории потребности населения регионов в инфраструктурном обеспечении, 226, стр. 117-133.
Погребова, О.А., Конников, Е.А. and Юлдашева, О.У., 2017. Нечетко-множественная модель оценки индекса развития устойчивого маркетинга компании. In Международная конференция по мягким вычислениям и измерениям. Федеральное государственное автономное образовательное учреждение высшего образования Санкт-Петербургский государственный электротехнический университет ЛЭТИ им. ВИ Ульянова (Ленина), 2, стр. 522-525
Родионов, Д., Пашинина, П., Конников, Е., 2022. Квантификаторы информационной среды финансового рынка. Экономические науки, 211, стр. 125-128.
Родионов, Д., Конников, Е., Конникова, О. [и др.], 2024. Влияние социально-экономических факторов на проникновение интернет-маркетинга в различных странах. Мягкие измерения и вычисления, 74 (1-1), стр. 48-61.
Родионов, Д., Конников, Е., Пашинина, П., Шаныгин, С., 2024. Тематическое моделирование информационной среды медиакомпаний: инструментальный комплекс LDA-TF-IDF. Мягкие измерения и вычисления, 76 (3), стр. 72-84.
Седых, Н., Корпош, Е. and Гончарова, Е., 2015. Причины социально-экономической поляризации регионов России. Экономика и современный менеджмент: теория и практика, (10-11-2 (53)), pp.136-140.
Титкова, И., 2017. Индекс Херфиндаля и индекс энтропии как показатели диверсификации экономики. Мировой опыт и экономика регионов России, стр. 375-377.
Тырсин, А., 2016. Энтропийное моделирование многомерных стохастических систем.
Швец, И., 2013. Минимизация энтропии при управлении инновационным развитием социально-экономической системы. Экономическая политика: на пути к новой парадигме, стр. 110-116.

The article was submitted 24.09.2024, approved after reviewing 09.10.2024, accepted for publication 16.10.2024.

Статья поступила в редакцию 24.09.2024, одобрена после рецензирования 09.10.2024, принята к публикации 16.10.2024.

About authors:

1. Elena Velichko, Head of the Department for External Relations, Marketing and Advertising, Baltic State Technical University "Voenmekh" named after. D. F. Ustinova, St. Petersburg, Russian Federation. velichko_ed@voenmeh.ru

2. Prokhor Polyakov, laboratory assistant at the Higher School of Engineering and Economics, Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russian Federation. prohor@polyakov-box.ru

Информация об авторах:

3. Елена Величко, начальник управления по внешним связям, маркетингу и рекламе, Балтийский государственный технический университет «Военмех» им. Д. Ф. Устинова, Санкт-Петербург, Российская Федерация. velichko_ed@voenmeh.ru

4. Прохор Поляков, лаборант Высшей инженерно-экономической школы, Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Российская Федерация. prohor@polyakov-box.ru

Research article
DOI: https://doi.org/10.48554/SDEE.2024.3.4

Formation of an Approach to Improving Regional Competitiveness in the Russian Federation

Grigory Kulkaev*

Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russian Federation, kulkaev_g@spbstu.ru
*Corresponding author: kulkaev_g@spbstu.ru

Abstract

Today, in order to develop national economies, it is necessary to pay attention to the economies of the regions of the countries. The regional economy is the basis of the national welfare. In the Russian Federation there are a number of problems with regional development, one of which is the differentiated development of the constituent entities of the Russian Federation. Every year, the difference in development increases due to the rapid growth of large economic regions and the lag in regions removed from the central regions. In the context of such key competition factors, this development becomes competitive in the region. The article examines various concepts of and approaches to regional competitiveness that contribute to the formation of comprehensive economic cooperation. Through analysis of statistics on indicators of the socio-economic development of some regions of the Russian Federation, the reason for the observed disproportion was identified. This reason is the outflow of population. A person with strength and skills is a key part of building a regional economic system. To solve problems that arise in the work, a model for increasing regional competitiveness is proposed, which includes three stages. The first is basic, focusing on building the foundations of production; the second stage involves focusing on the development of science and education; and the third is creative, focused on the development of creative industries. Thus, the model proposed by the author meets the criterion of complexity, as well as the requirements for increasing the competitiveness of regions in the medium and long term, which will contribute to the socio-economic development of the constituent entities of the Russian Federation, balance and balance in the level of development of the country as a whole.

Keywords: regional competitiveness, regional economy, differentiated development, complexity

Citation: Kulkaev, G., 2024. Formation of an Approach to Improving Regional Competitiveness in the Russian Federation. Sustainable Development and Engineering Economics 3, 4. https://doi.org/10.48554/SDEE.2024.3.4

Научная статья
УДК 332.1
DOI: https://doi.org/10.48554/SDEE.2024.3.4

Формирование Подхода к Повышению Региональной Конкурентоспособности в Российской Федерации

Григорий Кулькаев*

Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Россия, kulkaev_g@spbstu.ru
*Автор, ответственный за переписку: kulkaev_g@spbstu.ru

Аннотация

Сегодня в целях устойчивого развития экономик государств необходимо уделять внимание экономиках регионов этих стран. Региональная экономика является фундаментов, на котором держится национальное благосостояние. В Российской Федерации сегодня наблюдается ряд проблем в контексте регионального развития, одной из таких проблем является дифференцированное развитие субъектов Российской Федерации. С каждым годом разница в развитии увеличивается за счет быстрого роста крупных экономических регионов и отставания в развитии отдаленных от центра регионов. В таких условиях ключевым инструментом для выравнивания этого развития становится конкурентоспособность региона. В статье рассмотрены различные концепции и подходы региональной конкурентоспособности, которые будут способствовать формированию комплексного подхода. В ходе анализа статистических показателей социально-экономического развития некоторых регионов Российской Федерации была выявлена причина наблюдающихся диспропорций. Этой причиной является отток населения. Человек обладая определенными ресурсами, навыками и умениями является ключевым звеном в построении региональной экономической системы. Для решения данной проблемы в работе предлагается модель подхода к повышению региональной конкурентоспособности, которая включает в себя три стадии. Первая – базовая, нацелена на построение основ производства, вторая стадия нацелена на развитие науки и образования, третья – творческая, нацелена развитие креативных индустрий. Таким образом, предлагаемая автором модель соответствует критерию комплексности, а также призвана повысить конкурентоспособность регионов в среднесрочной и долгосрочной перспективе, что будет способствовать социально-экономическому развитию субъектов Российской Федерации, стабилизации баланса и выравниванию уровня развития по стране в целом.

Ключевые слова: региональная конкурентоспособность, региональная экономика, дифференцированное развитие, комплексность

Цитирование: Кулькаев, Г., 2024. Формирование Подхода к Повышению Региональной Конкурентоспособности в Российской Федерации. Sustainable Development and Engineering Economics 3, 4. https://doi.org/10.48554/SDEE.2024.3.4

1. Introduction

Today, the integrated, balanced development of regions is an urgent issue throughout the world. The modern world is faced with many barriers to such development, including international sanctions, military operations, and increased multipolarity, among others. In these conditions, there is a tendency for countries of 'second and third rank' (countries in Africa, South America, Asia) to enter onto the world stage, increasingly gaining importance on international platforms. Despite the positive results from increasing their contributions to the world economy, many of these countries encounter the problem of a low level of competitiveness within their territories, which in turn slows down the growth rate of their national economies.

At present, the Russian Federation is one of the key countries around which an integrated economic system is being formed. Russian resources, production, and the results of the results of related activities are involved in the economies of many foreign countries. Russia is the main supplier of wood, oil products, uranium, to many countries, without which they could not ensure the stability of their economies (Yu and Feng, 2023). In addition, the Russian Federation participates in many projects within the framework of international associations (EAEU, BRICS, SCO, etc.), as well as within the framework of bilateral agreements (for example, the construction of nuclear power plants in Turkey and Belarus). These facts confirm the importance of Russia in the international arena; however, some economists note that, despite its obvious success in world markets, Russia has a number of internal barriers that hinder full development. One of these problems is the low level of competitiveness of Russian regions (Gadzhiev et al., 2022).

For more than ten years, the Government of the Russian Federation has been implementing various state programs, projects, concepts, plans, but, as the authors have found, this has not produced effective results (Korovin, 2021). The authors note that the economic growth of many Russian regions does not keep pace with the growth of the national economy and global trends. Due to their scale and the complexity of the administrative-territorial division of the country, those measures to increase regional competitiveness that can work effectively in other countries cannot be implemented in Russia with the same effect (Kulkaev et al., 2022). Hence the need arises for the formation of a different approach to increasing the competitiveness of Russian regions.

Thus, the object of the current research is the regional economy of the constituent entities of Russia and the competitiveness of these regions. The goal of this work is to develop an integrated approach to increasing the regional competitiveness of the constituent entities of the Russian Federation. The tasks include conducting a literature review on the topic of regional competitiveness, analysing the main economic indicators of Russian regions, analysing the reasons for the low level of regional competitiveness, formulating the main problems, and developing comprehensive solutions aimed at eliminating problems and increasing regional competitiveness.

The novelty of the research lies in the formation of an integrated approach to increasing the competitiveness of Russian regions regarding the unresolved problems of integrated regional development.

2. Literature Review

V.A. Velkova notes that 'regional development is a mode of functioning of the region, focused on the positive dynamics of all the main parameters of the standard of living, which is ensured by the sustainable and balanced reproduction of economic potential, resource, economic, socio-demographic potential' (Velkova, 2009).

The term regional development applies to many areas: economic development, social development, human development, etc. In all cases, a positive movement of some indicators of the sphere is implied—for example, the growth of gross regional product, the growth of household incomes, and an increase in production rates. However, if we observe a decrease in regional development we will observe not progress, but regression.

Problems related to regional development are some of the most important issues of a regional economy. Many researchers have been trying to address these problems for several years. Table 1 presents the main problems of regional development outlined by scientists in the literature.

Table 1. Scientific ideas regarding problems of regional development

№	Author	Identified problems
1.	N. Medvedeva, E. Frolova, O. Rogach, T. Ryabova	The main problem of regional development is regional inequality. The author notes a defect in the system of interbudgetary relations aimed at political benefits. As a result, the author notes the problem of poor resource provision, primarily human resources and potential (Vladimirovna et al., 2021).
2.	A. Bogoviz, G. Chernukhina, L. Mezhova	The authors note that the main problems are the insufficient levels of production caused by the scientific and technical lag of the regions (Bogoviz et al., 2018).
3.	T. Uskova	The author notes two significant problems of regional development: unequal regional tax rates and rapid environmental change. Regarding the first problem, the author emphasises that high tax rates infringe on small and medium-sized businesses, which are the basis of the regional economy. The second problem is that today there is a rapid transformation of the economy, for which not all regions are ready due to the digital lag (Uskova, 2023).
4.	K. Samkov	The author sees the main problem of regional development as a poorly developed transport infrastructure, which becomes a challenge for industrial exchange between regions and, as a result, limits regions' cooperation and mutual assistance in economic development (Samkov, 2021).
5.	A. Evstafieva	The author focuses on the compactness of the developed space of Russia and the concentration of the population in the European part. These problems lead to imbalances in the distribution of labour resources and demographic reproduction (Evstafieva, 2023).
6.	A. Sapiev, N. Galinskaya	The authors note the importance of all the above problems, but in their research they delve into the root of these problems, namely the mechanism of regional governance. They note the obsolescence of the existing system of state and municipal management in Russia and propose to transform it into project management, which responds more quickly to the influence of external factors (Sapiev and Galinskaya, 2022).

Source: Compiled by the author

From the analysis it is clear that all problems directly or indirectly result from an imbalance in the regional economy. Some regions are developing rapidly, while others are remaining stagnant from year to year, and still others are regressing. In the latter regional economic systems, of course, there will be no stable growth of the national economy.

The problem of uneven regional development has always been acute for the Russian Federation. Being a large state that includes 89 constituent entities, it is difficult to achieve balanced development of the regions and avoid a large gap in development, although each region has unique resource potential (Eremina and Rodionov, 2023).

Imbalance in regional development is the cause of many other problems that regions face—for example, population outflow, scientific and technological underdevelopment, and declining labour potential (Rodionov et al., 2023).

In such conditions, issues of regional competitiveness are often raised, which is designed to increase the pace of regional development.

To understand the necessary approach to increasing regional competitiveness, we propose to first analyse the literature on various concepts of regional competitiveness.

The concept of regional competitiveness belongs to the modern period of economic science. Regional competitiveness, as a branch of economic science, was conceptualised in the second half of the 20th century, but some of its provisions were present in the works and ideas of earlier scientists.

First, one must understand the very concept of competition. It is often defined in encyclopaedic dictionaries as rivalry, competition, and clash of interests. In economic encyclopaedias, competition is understood as the struggle of entrepreneurs to make a profit by utilising the most favourable conditions for the production and sales of products, characteristic of commodity production, the basis of which is private ownership of the means of production (Kichigin et al., 2023).

Today there are two main concepts: classical and neoclassical. Within the framework of the classical concept, there are two approaches. The first is resource based, proposed by W. Christaller, N.N. Kolosovsky, A. Losch, and M.K. Bandman. The basis of this approach is the competent and rational distribution of resources, production forces, sales markets, etc. Thus, W. Christaller, within the framework of this theory, divides a region into three administrative units according to hierarchy. Larger administrative units become large centres, and smaller units are already formed around them, thus forming an agglomeration. Notably, these scientists built this theory on an assumption within the framework of behavioural economics. The basis for constructing a model for the location of central places is the ‘behavioural’ principle of a minimum of time, effort, and money necessary for residents of peripheral settlements to purchase goods in a central place (Dzhurka, 2023). Theory N.N. Kolosovsky aimed to create a rational system of territorial planning, minimising transport costs and maximising the use of the comparative advantages of economic regions using a centralised system of planning targets. The complication of a country’s territorial structure modified Kolosovsky’s concept; an economic subdistrict was added, which was later called the territorial production complex (Sherin, 2019).

The second approach within the framework of the classical concept is investment innovation It essentially implies the results of the implementation of the resource-based concept. Some researchers believe that the influx of investment is the result of actions related to resource allocation planning (Bun’kovskij and Samaruha, 2014). The main feature of this approach is the ability to assess the competitiveness of a region. If factors such as spatial development and resource allocation are difficult to assess, as they are highly complex, which is difficult to achieve taking into account the action of behavioural principles in the concept, then indicators of investment activity are quite easy to statistically analyse. Later researchers have expanded the concept with an innovative component, arguing that investment generates strong economic development. Among this set of developed regions, innovation activities can distinguish some regions from others. Thus, further distinguish ‘the innovative competitiveness of a region is the region’s position in competitive markets, determined by the ability to effectively use the results of innovation activities to improve the level and quality of life of the population’ (Kichigin et al., 2023).

Within the framework of the neoclassical concept, two approaches have also been proposed: humanistic and creative. The humanistic concept of regional competitiveness lies in the importance of human capital as the foundation for the development of industry, production, etc., in a regional economy. Indeed, without human participation, no production enterprises can operate; without the work of enterprises in the real sector, there will be a decline in the given region’s economy. As a result, the region will withdraw from competition, and the population will begin to migrate from this region, ceding its potential to neighbouring territories (Hao, 2021). O. Donskikh believes that the education of a region’s population is the basis of its competitiveness, since education drives the development of industry and production, attraction of investments, and development of innovations (Donskikh, 2023). Thus, O. Donskikh emphasises that without people it is impossible to implement the classical concept, wherein people and their resources are the basis of the region’s economy, and therefore its competitiveness. R.A. Dzhumaeva builds on Donskikh’s ideas. In her works, R.A. Dzhumaeva posits the idea of the importance of human education for the development of regional and national economies. As a result of education, the author saw the growth of research projects, design bureaus, etc., which then give rise to the development and implementation of innovations in the real sector of the economy (Dzhumaeva et al., 2018).

If the scientific and educational foundations have received the greatest development in the CIS countries, Asia and Africa, then a slightly different view of human resources is most common today in Europe and America. Richard Florida has further developed related theory. He has moved away from the idea of the importance of educating a region's population towards encouraging creativity in a population's economic activities. In his works, he refers to the 'creative class' as the part of the population involved in music, entertainment, etc. He considers this class to be a region's competitive advantage in regional development (Mack, 2022).

Jason Potts is also a proponent of this idea. In his opinion, today, an economic base has already been formed in all regions: natural resources have been developed, there are functioning enterprises, there are sales markets. When all regions have established the basic components of an economy, o there can be no competition among regions, since everyone is on the same footing (Hodgson, 2021).

According to these authors, the competitive advantage of each region is thus human creativity. Therefore, modern "ideas of regional competitiveness have moved away from the real sector of the economy, not only to intangible benefits, but also to those that are aimed at satisfying higher needs (according to Maslow)—self-actualisation and self-realisation (Weidman, 2023).

3. Materials and Methods

This article aims to consider the degree of differentiation in the socio-economic development of the regions of the Russian Federation. Due to the limited availability of statistical data, the study has been conducted in 85 regions of Russia. As part of this stage of the study, it is proposed to assess the differences in the dynamics of some socio-economic indicators of macroregions and indices, and draw intermediate conclusions. Next, it is necessary to identify the reasons for the imbalance in regional development, build a hypothesis, and prove its reliability.

Based on the statistical indicator carried out, this article develops an integrated approach, including a model, to increasing regional competitiveness, considering existing concepts and the degree of their applicability and necessity in the resulting situation. Thus, the research methodology can be divided into the following steps:

Step 1: Analyse static indicators of the socio-economic development of macroregions and the identified 85 Russian regions.

Step 2: Analyse the economic situation that caused the growth of imbalance in economic development.

Step 3: Study and research existing principles and approaches to increasing regional competitiveness, assessing their applicability to the identified reasons.

Step 4: Construct an abstract model of an approach to increasing regional competitiveness.

All statistical data are taken from the collection of the Federal State Statistics Service of Russia's 'Regions of Russia. Socio-economic indicators'.

4. Results

As part of the statistical analysis of socio-economic indicators, it is necessary to consider the values of the gross regional product per capita, the level of employment of the population, the per capita monetary income of the population, and investments in fixed capital per capita. These indicators, of course, do not fully reflect the socio-economic development of the regions but are considered key for assessing the degree of this development. As an object of study, the following macroregions, or federal districts, of the Russian Federation have been considered: Central Federal District (CFD), Southern Federal District (SFD), Northwestern Federal District (NWFD), Far Eastern Federal District (FEFD), Siberian Federal District (SiFD), Ural Federal District (UFD), Volga Federal District (VFD), and North Caucasus Federal District (NCFD). Consider the graph in Figure 1.

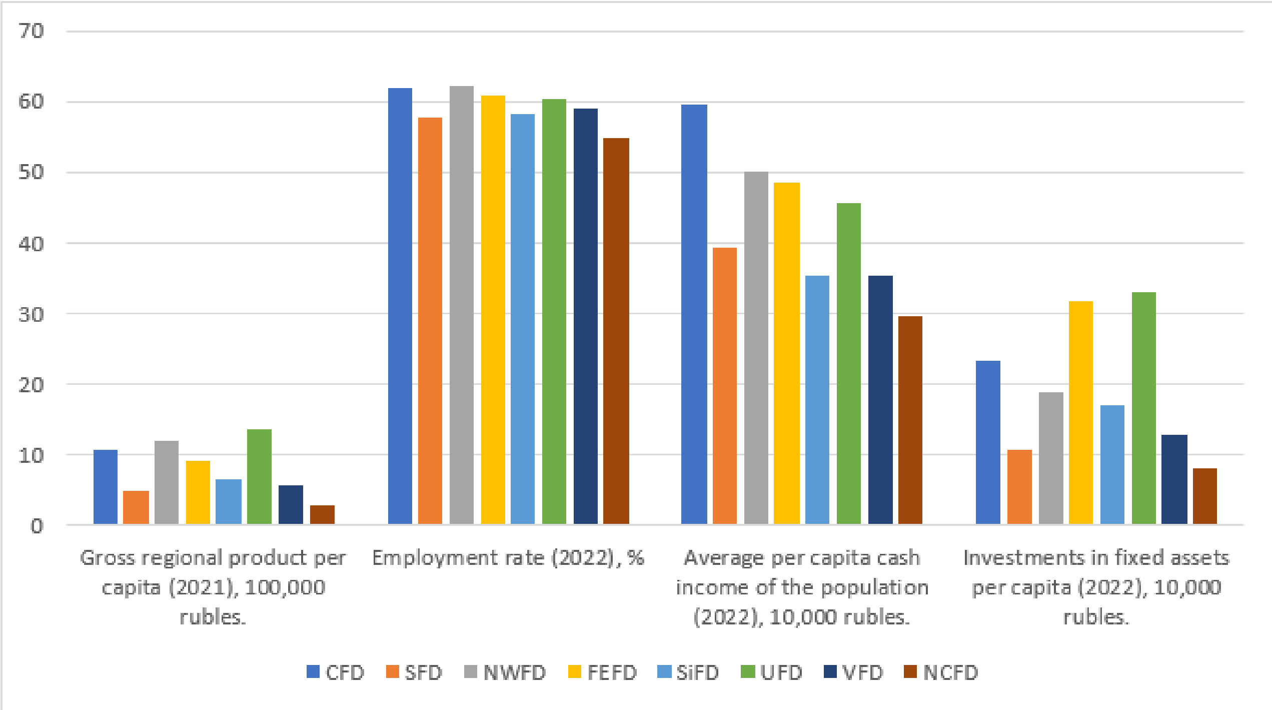

Figure 1. Analysis of the main socio-economic indicators for macro-regions of Russia

Source: Compiled by the authors

Based on this graph, it is notable that Russia's macroregions have an imbalance in development. First, the imbalance in the gross regional product per capita should be noted. Gross regional product is the main indicator by which the economic development of territories can be assessed. As shown in the graph, the highest value is observed in the Ural District, while the lowest is in the North Caucasus District. Thus, the level of development in terms of this indicator varies by a factor of 4 across amplitude macroregions. There are also disparities in other indicators. The difference in the volume of investments per capita reaches 3.2 times, in terms of average per capita income of the population - 2 times. The smallest imbalance is observed in the employment level indicator.

At first glance, it may seem that the resulting imbalance in socio-economic development is not significant. However, it is worth considering that at this stage of the study, generalised statistics for the macro-regions of the country are presented. The most accurate picture appears when analysing the level of development within the regions themselves.

To assess the socio-economic development of regions and assess imbalances in development, various integral indices are often used. One of the most optimal in this area is the rating of the socio-economic status of Russian regions, which is determined according to RIA rating which is based on the calculation of the integral index of the socio-economic development of the included regions.

The rating is based on data from Rosstat, the Ministry of Finance and the Federal Treasury. The indicator system is divided into 4 groups:

• Indicators of the scale of the economy: volume of production of goods and services, consolidated budget revenues, number of people employed in the economy, retail trade turnover.

• Indicators of economic efficiency: volume of production of goods and services per capita, investment in fixed capital per capita, share of profitable enterprises, level of tax collection.

• Indicators of the budgetary sphere: consolidated budget revenues per capita, share of tax and non-tax revenues in the total volume of consolidated budget revenues, ratio of public debt to tax and non-tax revenues of the consolidated budget, ratio of tax and non-tax revenues of the consolidated budget to consolidated budget expenditures.

• Indicators of the social sphere: ratio of population income to the cost of a fixed set of consumer goods and services, unemployment rate, life expectancy at birth, infant mortality rate, mortality rate of the working age population, share of the population with incomes below the poverty line.

Figure 2 shows a map of the Russian Federation divided into regions and colour coded according to their socio-economic status index values for 2022, where 1 is the maximum index value, and 0 is the minimum index value.

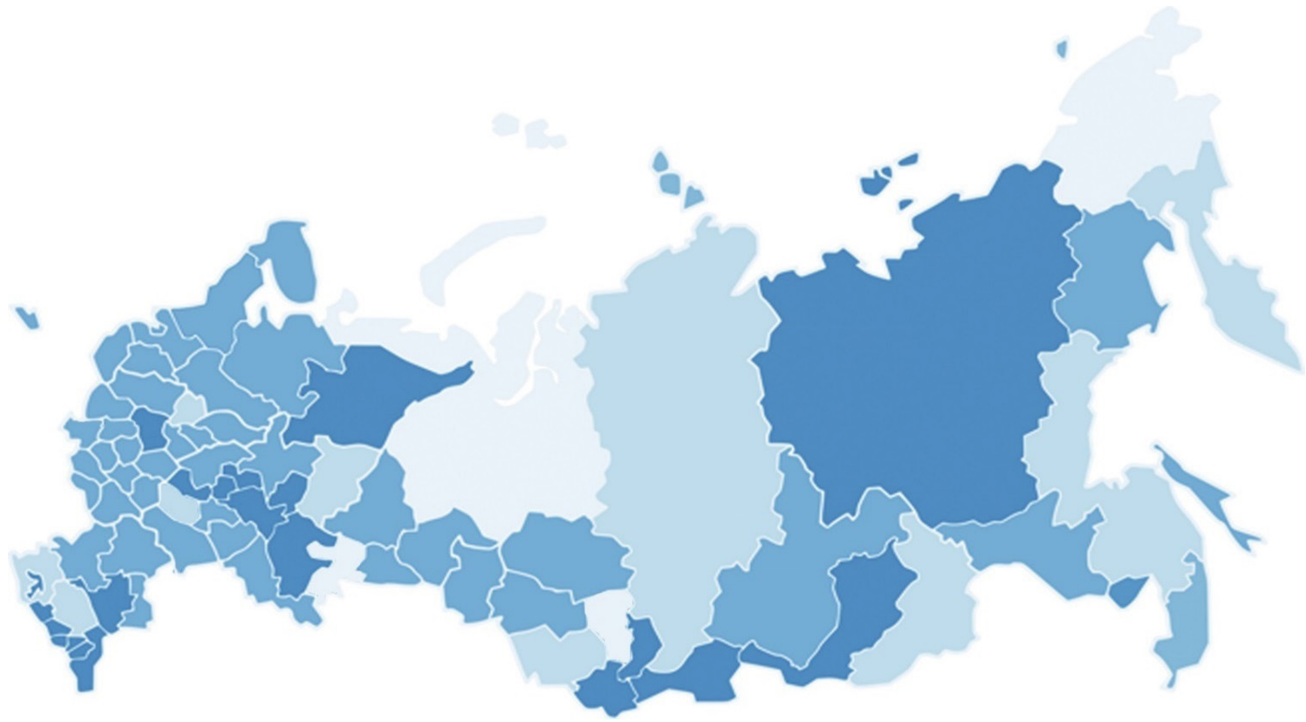

Figure 2. Map of the differentiation of development of Russian regions

Source: Compiled by the author

This map shows the socio-economic status of 85 regions of Russia, as there are no calculations yet available for the remaining regions. Regions with darker colours have higher levels of socio-economic development, while regions with lighter colours, moving towards white, have lower levels of development.

Thus, this figure shows us that there are about 20 regions with a high level of socio-economic development and more than 16 regions with a critically low level of development, while the rest have an average leve. This fact reaffirms the presence of imbalances in the development of regions of the Russian Federation. In keeping with this, the regions of the Ural Federal District (in the central part of the map) and the Far Eastern Federal District (right side of the map) show the lowest levels of socio-economic development.

Today, in the lagging regions of the Russian Federation, there is a problem of labour shortages in the presence of production capacities, jobs, etc. (Mozaleva et al., 2023).

Some researchers of regional economic problems note that this fact is associated with the outflow of population from lagging regions to more developed ones (Okrepilov et al., 2021).

Indeed, in Russia today, the following trend can be observed: the younger generation is leaving their native regions for more developed ones to obtain education; most of them, after completing their studies, stay in these regions, find jobs, and have families and children. Thus, such a trend contributes to the development of some regions (regions receive young personnel and new families, increase their production, etc.) but deprives other regions of development opportunities (regions lose human resources, reduce industrial production, etc.).

To confirm this hypothesis, it is necessary to consider regional indicators related to population and human resources. To do this, considering the population size (million people) for the period from 2005 to 2022 in order to assess the provision of regions with human resources is required. For analysis, 'receiving' regions (Moscow, St. Petersburg, Republic of Tatarstan) and 'giving' regions (Yamalo-Nenets Autonomous Okrug, Jewish Autonomous Region, Sakhalin Region) can be considered. The results are presented in Figure 3.

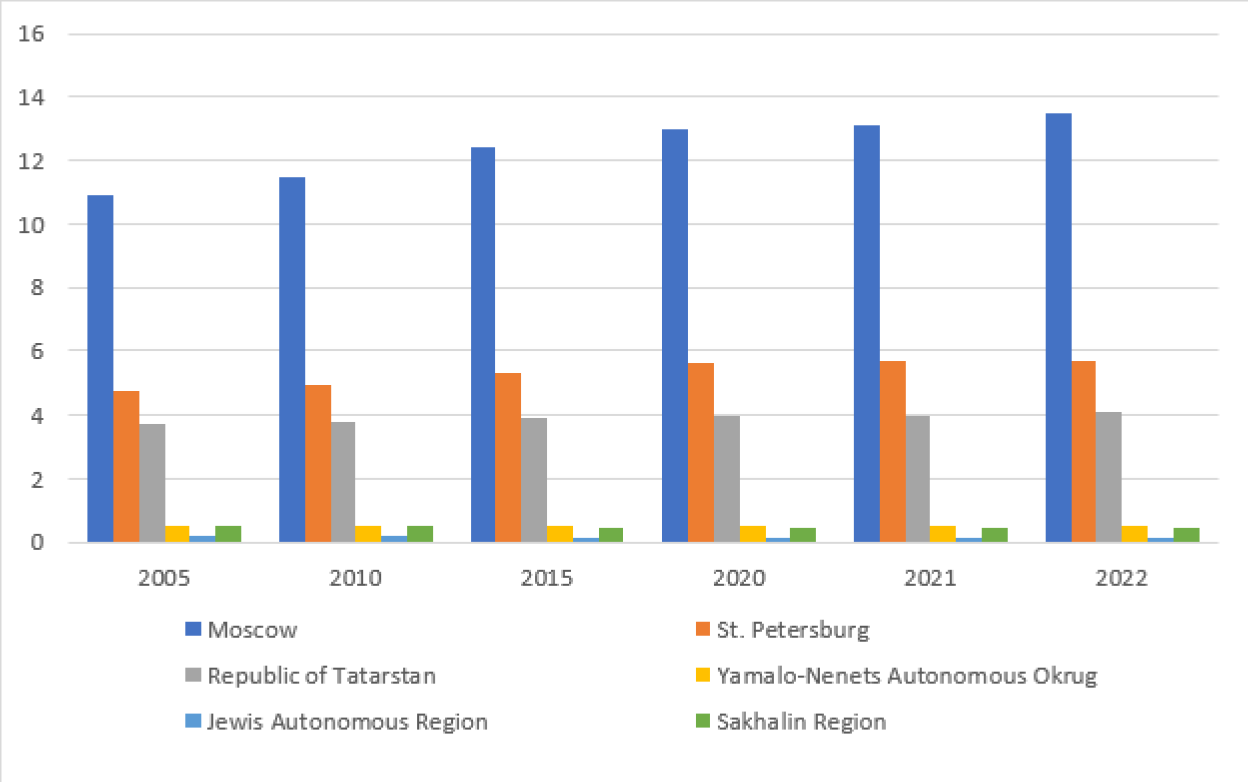

Figure 3. Population dynamics of selected regions (million people)

Source: Compiled by the author

This graph clearly shows that while in economic centres (Moscow, St. Petersburg, and Tatarstan) the population is increasing, in lagging regions, the population is declining. Of course, this graph does not yet confirm the hypothesis that people from some regions are moving to others. It is useful to consider another graph for the same regions, showing the rate of migration growth per 10,000 people (Figure 4).

Sustain. Dev. Eng. Econ. 2024, 3, 4. https://doi.org/10.48554/SDEE.2024.3.4

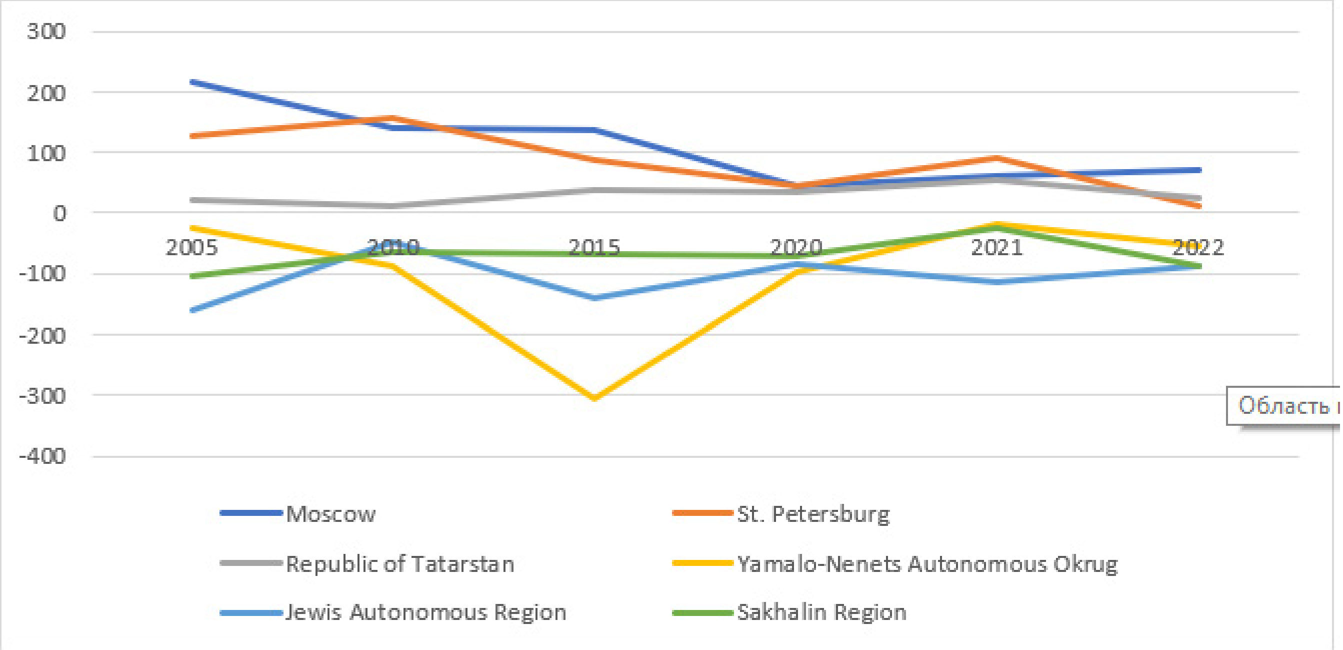

Figure 4. Dynamics of natural migration growth according to selected indicators (thousand people)

Source: Compiled by the author

This graph already shows that in developed regions, the migration growth rate is always positive, despite the decline in recent years caused by the coronavirus pandemic. In other regions, there is a constant negative value of this indicator—that is, more people are leaving the region than are arriving.

As the All-Russian Center for the Study of Public Opinion notes, the main reasons for leaving the regions are low wages and a low standard of living in general. Moreover, among the younger generation, a common reason for leaving is the low quality level of education, limited range of areas of training, and lack of openings available in educational institutions.

If today it is already difficult to retain the adult working population in lagging regions, since it is almost impossible in the short term to dramatically improve the quality of life of the population, this process requires time, a competent step-by-step approach, then it remains possible to retain the younger generation locally and attract it from the outside.

Analysing the approaches presented within the framework of the concepts of regional competitiveness, the importance of each of the presented views for solving problems of regional development is noteworthy. This paper proposes the development of an integrated approach to increasing the competitiveness of regions faced with the problem of population outflow. Figure 5 presents an abstract model of an approach to increasing regional competitiveness.

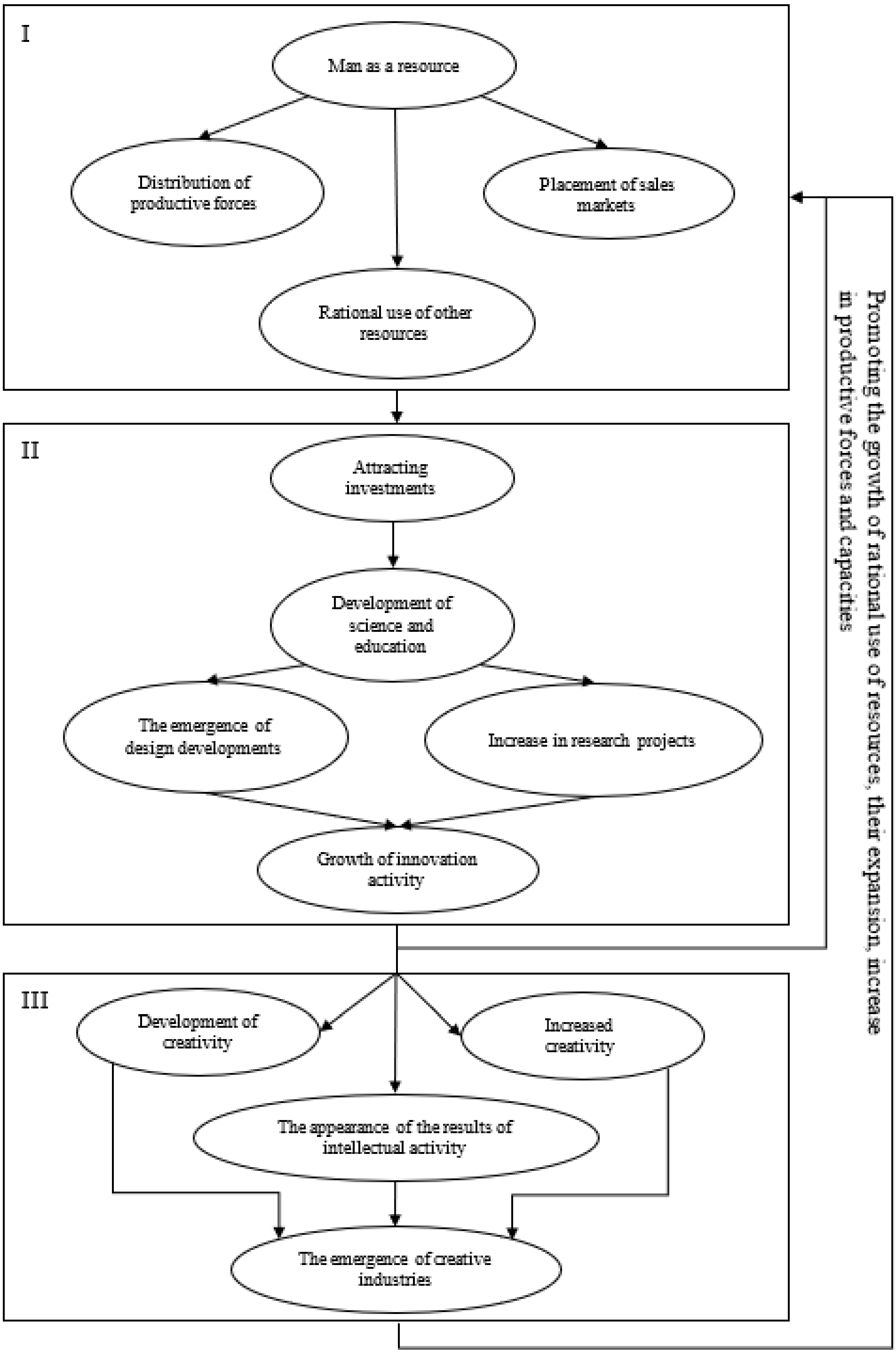

Figure 5. Model of an integrated approach to increasing regional competitiveness

Source: Compiled by the author

The presented model symbolises an integrated approach to increasing regional competitiveness, consisting of three stages. The first stage includes initial actions to develop the region's economy. Here, a person acts as the initiator of this development. With a person acting as both a resource and a subject of management with a certain set of skills, it is from a person that the initiative for the distribution of productive forces, the placement of a sales market, and the use of other resources comes. This stage reflects the classical ideas of regional competitiveness, which are based on the competent and rational planning of a territory. Some researchers have noted that today all regions of the Russian Federation have already implemented this stage, since economic processes are present and functioning in each region. The greatest difficulties for lagging regions arise in the implementation of the proceeding stages.

Thus, the second stage includes selecting the correct vector for further development. Within the framework of this model, after planning and establishing production, it is implied that investments will be attracted both from commercial organisations and from the state represented by the federal government into the economy of the region. The regional authorities must then determine the optimal area for investing these funds. Accounting for the specifics of the outflow of the younger generation in the Russian Federation, investing in the development of education and science is proposed. This measure will allow us to develop high-tech designs and conduct research work. All this will contribute to maintaining the local population. In addition, this measure will contribute to the development of innovation and innovative activity in the region, the results of which can be implemented in the functioning of production facilities in the territory.

After the material foundations of the socio-economic development of the region have been implemented, there will be a need for the emergence of new forms of human activity. One of these forms is creativity and intellectual activity, serving as a platform for the introduction and development of creative industries, which today is a powerful impetus for the development of regional economies. Thus, the population remaining in the region, having received a high-quality education and comfortable working conditions here, will develop the foundations of their activities in new forms that will in turn lay the foundation for the development of a new approach to socio-economic development—that is, a creative approach. The implementation of these measures will again be implicated in the functioning of sales markets, productive forces in the region, and so on.

Thus, the proposed approach model for increasing regional competitiveness will contribute not only to the socio-economic development of the region in the medium term but will also lay new foundations for economic development in the long-term context.

5. Discussion

Nevertheless, the results of the present work cannot be considered ideal and final. First, we would like to note the views of a number of scientists regarding the application of an approach based on creativity and creativity. Some authors indicate that creative industries cannot be a significant component of a regional economy, since any strong economic system is based primarily on the real sector (Gutman and Brazovskaia, 2023). In addition, some authors do not classify the creative sphere as comprising economic activities at all (Kichigin and Gonin, 2020). However, it is worth understanding that to implement the criterion of complexity when developing this approach, it is important to consider all possible theoretical concepts.

Additionally, some authors argue that a smooth transition from one stage to another is quite difficult to implement from the point of view of the apparatus of state and municipal governments (Surjana et al., 2020). Due to the high degree of variability of external conditions, there is a frequent change in the goals and objectives of public administrations, which obliges the adjustment of the original plans (Ivanova et al., 2023). However, here it is worth because increasing regional competitiveness is aimed at overall socio-economic development to maintain economic stability in the region and an adequate quality of life for the population. Therefore, the implementation of this model approach will be relevant regardless of external factors. The presented model is characterised by its complexity and stability, as well as relevance in the context of changes in the external environment and the goals and objectives of the region's leadership.

6. Conclusion

This article raises the issue of developing an approach for increasing regional competitiveness. The article also includes a literature review, making it possible to define the concept of regional development and identify the problems of such development, which can be summarised as an imbalance in the socio-economic development of territories. Regional competitiveness is here proposed as one of the tools for accelerating the pace of this development. Furthermore, the literature review examines various concepts of and approaches to increasing regional competitiveness. The classical concept includes resource and investment-innovation approaches, while the neoclassical concept includes human and creative approaches.

Based on the literature review, a hypothesis was constructed about the presence of imbalances in the regional development of the constituent entities of the Russian Federation. This hypothesis was then confirmed by the analysis of statistical data in the field of socio-economic development. Using an analysis of statistics and the opinions of scientists, we concluded that disproportions in development are associated with the outflow of the population to more developed regions. To address this problem, the work proposes a model of an integrated approach to increasing regional competitiveness.

This model consists of three successive stages. In the first stage, address are formed. In the second stage, the attracted investments are used in the development of science and education in order to preserve the population of the younger generation locally and to promote the development of innovations, which will subsequently be used to develop those productive forces that were formed during the first stage. The third stage includes the development of creative industries, which can also complement the region's economy with new resources, performance results, and markets. Thus, based on the points considered above, we can conclude that the objectives and purpose of the study were achieved in full.

References

Bogoviz, A.V., Chernukhina, G.N., Mezhova, L.N., 2018. Subsystem of the territory management in the interests of solving issues of regional development. Quality—Access to Success 19.

Bun'kovskij, V.I., Samaruha, A.V., 2014. Management of production processes in terms of economic risks. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.2539001

Donskikh, O., 2023. Where did the crisis come from? The view of a provincial. Reflections on Vadim Radayev's book 'Education in crisis.' Science Management: Theory and Practice 5. https://doi.org/10.19181/smtp.2023.5.2.19

Dzhumaeva, R., Gadzhiev, E., Styazhkina, E., 2018. Klasternyj podhod v upravlenii chelovecheskim kapitalom v interesah innovacionnogo razvitiya regiona [Cluster approach to human capital management in the interests of innovative development of the region]. Bulletin of Kemerovo State University. Political, Sociological and Economic Sciences Series 3, 87–92.

Dzhurka, N.G., 2023. Hierarchical structures of national economic spaces: The general and the particular. Spatial Economics 19. https://doi.org/10.14530/se.2023.4.018-057

Eremina, I., Rodionov, D., 2023. The special aspects of devising a methodology for predicting economic indicators in the context of situational response to digital transformation. International Journal of Technology 14. https://doi.org/10.14716/ijtech.v14i8.6839

Evstafieva, A.K., 2023. Concepts of spatial development and problems of regional economy. Innovatsionnoe razvitie ekonomiki. https://doi.org/10.51832/22237984202327

Gadzhiev, Y.A.O., Timushev, E.N., Styrov, M.M., 2022. Dynamics of competitiveness of the Northern Regions in 2008–2020: Development of an assessment methodology. Economy of Regions 18. https://doi.org/10.17059/EKON.REG.2022-4-4

Gutman, S., Brazovskaia, V., 2023. Tool development for assessing the strategic development of territorial socio-economic systems for the purposes of energy sector Digital Transformation. Energies (Basel) 16. https://doi.org/10.3390/en16145269

Hao, Q., 2021. Rethinking the improvement of the compilation content and planning system of territorial spatial planning. Tropical Geography 41. https://doi.org/10.13284/j.cnki.rddl.003373

Hodgson, G.M., 2021. Debating the future of heterodox economics. J Econ Issues 55. https://doi.org/10.1080/00213624.2021.1945874

Ivanova, M., Kulkaev, G., Mozaleva, N., 2023. Smart workplace: Implementation of management innovations in public administration processes, in: Lecture Notes in Networks and Systems. https://doi.org/10.1007/978-3-031-47694-5_12

Kichigin, O., Gonin, D., 2020. Human capital as a catalyst for digitalization of regional economy, in: IOP Conference Series: Materials Science and Engineering. https://doi.org/10.1088/1757-899X/940/1/012030

Kichigin, O., Kulkaev, G., Mozaleva, N., Nazarova, G., 2023. Analysis of the impact of the socio-economic environment on innovative digital development of the North-Western Federal District of the Russian Federation, in: Lecture Notes in Networks and Systems. https://doi.org/10.1007/978-3-031-32719-3_8

Korovin, G.B., 2021. Efficiency of government support for the manufacturing sector in Russian industrial regions. Economy of Regions 17. https://doi.org/10.17059/EKON.REG.2021-4-15

Kulkaev, G., Mozaleva, N., Leontiev, D., 2022. Analysis of domestic and foreign experience of project management in the implementation of the concept of e-government [Analiz otechestvennogo i zarubezhnogo opyta proektnogo upravleniya v sfere realizacii koncepcii elektronnogo pravitel'stva]. Public Administration: Electronic Newsletter 92, 7–23. https://doi.org/10.24412/2070-1381-2022-92-7-23

Mack, B.L., 2022. From crisis to choices: Re-imagining the future in shrinking cities. The rise and fall of the Christian myth.

Mozaleva, N., Ivanova, M., Kulkaev, G., 2023. Model of state support for industrial parks as a tool for sustainable development. International Journal of Technology 14. https://doi.org/10.14716/ijtech.v14i8.6834

Okrepilov, V., Velychenkova, D., Kichigin, O., Grozavu, I., Miroslavskaya, M., 2021. Improving the quality of life of the population in St. Petersburg with the use of digital technology based on the concept of a smart city, in: ACM International Conference Proceeding Series. https://doi.org/10.1145/3527049.3527072

Rodionov, D., Grishacheva, A., Shmeleva, A., Chertes, P., Melnikova, Z., Markevich, V., Konnikov, E., Kryzhko, D., 2023. The information environment cluster distribution of the regional socio-economic systems in transition economy, in: Lecture Notes in Networks and Systems. https://doi.org/10.1007/978-3-031-32719-3_15

Samkov, K.N., 2021. Financing the implementation of national and regional projects: Problems and sustainable development directions. Finance: Theory and Practice 25. https://doi.org/10.26794/2587-5671-2021-25-4-24-36

Sapiev, A.Z., Galinskaya, N.N., 2022. Problem regions and state policy in the field of regional economy. New Technologies 17. https://doi.org/10.47370/2072-0920-2021-17-6-89-95

Sherin, E.A., 2019. The concept of a production cycle as a tool for regional analysis. Bulletin of Udmurt University. Biology, Earth Sciences Series 29. https://doi.org/10.35634/2412-9518-2019-29-2-310-318

Surjana, O., Siswoyo, M., Dedy, A., Krisbianto, S., 2020. Bureaucratic reform and empowerment of state civil apparatus in the face of the industrial revolution 4.0. Journal of Advanced Research in Dynamical and Control Systems 12. https://doi.org/10.5373/JARDCS/V12I2/S20201310

Uskova, T., 2023. Current problems of regional development and ways to overcome them. Problems of Territory's Development [Проблемы развития территории]. https://doi.org/10.15838/ptd.2023.1.123.1

Velkova, V., 2009. Regional development and management of complex socio-economic development of a subsidized region [Regional'noe razvitie i upravlenie kompleksnym social'no-ekonomicheskim razvitiem dotacionnogo regiona]. Bulletin of ChSU 4.

Vladimirovna, M.N., Frolova, E.V., Vladimirovna, R.O., Mihaylovna, R.T., 2021. Public-private partnership in Russia: Problems of regional development. International Journal of Advanced and Applied Sciences 8. https://doi.org/10.21833/ijaas.2021.07.015

Weidman, N., 2023. Abraham Maslow, utopian realist. J Humanist Psychol 63. https://doi.org/10.1177/00221678211007670

Yu, Y., Feng, S., 2023. International trade cooperation between Russia and China under the Belt and Road Initiative in the new global order. Governance and Politics 2. https://doi.org/10.24833/2782-7062-2023-2-2-55-82

Список источников

Bogoviz, A. V., Chernukhina, G.N., Mezhova, L.N., 2018. Subsystem of the territory management in the interests of solving issues of regional development. Quality - Access to Success 19.

Bun'kovskij, V.I., Samaruha, A.V., 2014. Management of Production Processes in Terms of Economic Risks. SSRN Electronic Journal. https://doi.org/10.2139/ssrn.2539001

Donskikh, O., 2023. Where Did the Crisis Come From? The View of a Provincial. Reflections on Vadim Radayev's Book "Education in Crisis." Science Management: Theory and Practice 5. https://doi.org/10.19181/smtp.2023.5.2.19

Джумаева Р.А., Гаджиев Э.М., Стяжкина Е.И., 2018. Кластерный подход в управлении человеческим капиталом в интересах инновационного развития региона. Вестник Кемеровского государственного университета. Серия: Политические, социологические и экономические науки 3.

Dzhurka, N.G., 2023. Hierarchical Structures of National Economic Spaces: The General and the Particular N.G. Dzhurka. Spatial Economics 19. https://doi.org/10.14530/se.2023.4.018-057

Eremina, I., Rodionov, D., 2023. The Special Aspects of Devising a Methodology for Predicting Economic Indicators in the Context of Situational Response to Digital Transformation. International Journal of Technology 14. https://doi.org/10.14716/ijtech.v14i8.6839

Evstafieva, A.K., 2023. CONCEPTS OF SPATIAL DEVELOPMENT AND PROBLEMS OF REGIONAL ECONOMY. Innovatsionnoe razvitie ekonomiki. https://doi.org/10.51832/22237984202327

Gadzhiev, Y.A.O., Timushev, E.N., Styrov, M.M., 2022. Dynamics of Competitiveness of the Northern Regions in 2008–2020: Development of an Assessment Methodology. Economy of Regions 18. https://doi.org/10.17059/EKON.REG.2022-4-4

Gutman, S., Brazovskaia, V., 2023. Tool Development for Assessing the Strategic Development of Territorial Socio-Economic Systems for the Purposes of Energy Sector Digital Transformation. Energies (Basel) 16. https://doi.org/10.3390/en16145269

Hao, Q., 2021. Rethinking the Improvement of the Compilation Content and Planning System of Territorial Spatial Planning. Tropical Geography 41. https://doi.org/10.13284/j.cnki.rddl.003373

Hodgson, G.M., 2021. Debating the Future of Heterodox Economics. J Econ Issues 55. https://doi.org/10.1080/00213624.2021.1945874

Ivanova, M., Kulkaev, G., Mozaleva, N., 2023. Smart Workplace: Implementation of Management Innovations in Public Administration Processes, in: Lecture Notes in Networks and Systems. https://doi.org/10.1007/978-3-031-47694-5_12

Kichigin, O., Gonin, D., 2020. Human capital as a catalyst for digitalization of regional economy, in: IOP Conference Series: Materials Science and Engineering. https://doi.org/10.1088/1757-899X/940/1/012030

Kichigin, O., Kulkaev, G., Mozaleva, N., Nazarova, G., 2023. Analysis of the Impact of the Socio-economic Environment on Innovative Digital Development of the North-Western Federal District of the Russian Federation, in: Lecture Notes in Networks and Systems. https://doi.org/10.1007/978-3-031-32719-3_8

Korovin, G.B., 2021. Efficiency of Government Support for the Manufacturing Sector in Russian Industrial Regions. Economy of Regions 17. https://doi.org/10.17059/EKON.REG.2021-4-15

Кулькаев Г.А., Мозалева Н.И., Леонтьев Д.Н., 2022. Анализ отечественного и зарубежного опыта проектного управления в сфере реализации концепции электронного правительства. Государственное управление. Электронный вестник, 92, стр. – 7–23. https://doi.org/10.24412/2070-1381-2022-92-7-23

Mack, B.L., 2022. From Crisis To Choices: Re-Imagining The Future In Shrinking Cities. The Rise and Fall of the Christian Myth.

Mozaleva, N., Ivanova, M., Kulkaev, G., 2023. Model of State Support for Industrial Parks as a Tool for Sustainable Development. International Journal of Technology 14. https://doi.org/10.14716/ijtech.v14i8.6834

Okrepilov, V., Velychenkova, D., Kichigin, O., Grozavu, I., Miroslavskaya, M., 2021. IMPROVING THE QUALITY OF LIFE OF THE POPULATION IN ST. PETERSBURG WITH THE USE OF DIGITAL TECHNOLOGY BASED ON THE CONCEPT OF A SMART CITY, in: ACM International Conference Proceeding Series. https://doi.org/10.1145/3527049.3527072

Rodionov, D., Grishacheva, A., Shmeleva, A., Chertes, P., Melnikova, Z., Markevich, V., Konnikov, E., Kryzhko, D., 2023. The Information Environment Cluster Distribution of the Regional Socio-Economic Systems in Transition Economy, in: Lecture Notes in Networks and Systems. https://doi.org/10.1007/978-3-031-32719-3_15

Samkov, K.N., 2021. Financing the implementation of national and regional projects: Problems and sustainable development directions. Finance: Theory and Practice 25. https://doi.org/10.26794/2587-5671-2021-25-4-24-36

Sapiev, A.Z., Galinskaya, N.N., 2022. Problem regions and State policy in the field of regional economy. New Technologies 17. https://doi.org/10.47370/2072-0920-2021-17-6-89-95

Sherin, E.A., 2019. The concept of a production cycle as a tool for regional analysis. Bulletin of Udmurt University. Series Biology. Earth Sciences 29. https://doi.org/10.35634/2412-9518-2019-29-2-310-318

Surjana, O., Siswoyo, M., Dedy, A., Krisbianto, S., 2020. Bureaucratic reform and empowerment of state civil apparatus in the face of the industrial revolution 4.0. Journal of Advanced Research in Dynamical and Control Systems 12. https://doi.org/10.5373/JARDCS/V12I2/S20201310

Uskova, T., 2023. Current Problems of Regional Development and Ways to Overcome Them. Problems of Territory's Development / Проблемы развития территории. https://doi.org/10.15838/ptd.2023.1.123.1

Велкова В.А., 2009. Региональное развитие и управление комплексным социально-экономическим развитием дотационного региона. Вестник ЧГУ, 4.

Vladimirovna, M.N., Frolova, E.V., Vladimirovna, R.O., Mihaylovna, R.T., 2021. Public-private partnership in Russia: Problems of regional development. International Journal of Advanced and Applied Sciences 8. https://doi.org/10.21833/ijaas.2021.07.015

Weidman, N., 2023. Abraham Maslow, Utopian Realist. J Humanist Psychol 63. https://doi.org/10.1177/00221678211007670

Yu, Y., Feng, S., 2023. International Trade Cooperation between Russia and China under the Belt and Road Initiative in the New Global Order. Governance and Politics 2. https://doi.org/10.24833/2782-7062-2023-2-2-55-82

The article was submitted 20.09.2024, approved after reviewing 11.10.2024, accepted for publication 25.10.2024.

Статья поступила в редакцию 20.09.2024, одобрена после рецензирования 11.10.2024, принята к публикации 25.10.2024.

About author:

1. Grigory A. Kulkaev, assistant of the Graduate School of Public Administration, Institute of Industrial Management, Economics and Trade, Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russian Federation. https://orcid.org/0000-0001-5056-3520, kulkaev_g@spbstu.ru

Информация об авторах

1. Григорий Кулькаев, ассистент Высшей школы административного управления Института промышленного менеджмента, экономики и торговли, Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Россия, https://orcid.org/0000-0001-5056-3520, kulkaev_g@spbstu.ru

SECTION 4

MANAGEMENT OF KNOWLEDGE AND INNOVATION FOR SUSTAINABLE DEVELOPMENT

РАЗДЕЛ 4

УПРАВЛЕНИЕ ЗНАНИЯМИ И ИННОВАЦИЯМИ В ИНТЕРЕСАХ УСТОЙЧИВОГО РАЗВИТИЯ

Research article

DOI: https://doi.org/10.48554/SDEE.2024.3.5

The Application of Ontology-Based Game Theory for Decision Support in Sociotechnical Systems

Aleksei Gintciak*, Zhanna Burlutskaya, Darya Zubkova, Mikhail Uspenskiy

Peter the Great St. Petersburg Polytechnic University, Saint Petersburg, Russian Federation, aleksei.gintciak@spbpu.com, zhanna.burlutskaya@spbpu.com, daria.zubkova@spbpu.com, mikhail.uspenskiy@spbpu.com

*Corresponding author: aleksei.gintciak@spbpu.com

Abstract

The present paper develops an invariant ontology of strategic interaction in a sociotechnical system using game theory tools. In the course of the research, ontologies are considered tools for modelling sociotechnical systems, including tools for social and technical process integration. The demand for these tools derives from the need to integrate people into technical systems as equivalent and equal elements that exert both external and internal influence on the system. Such sociotechnical models have already been applied to describe enterprise information structures, but they lack a description of decision-making between the system elements within the strategic interaction. As part of the solution to this problem, an ontology-based model of a sociotechnical system describing the interaction of both social and technical elements through game interaction is developed. Each of the participants in the interaction is described in terms of game theory, with the allocation of possible strategies and the corresponding winnings. Through the interactive entities within the game theory model, game interaction takes place between the participant and appropriate behaviour strategy selection. The model is a flexible, scalable tool for building simulation models of sociotechnical systems. The results obtained will be tested when real sociotechnical systems are built, and the ontology will be refined according to the results obtained.

Keywords: game theory, digitalisation, ontology, sociotechnical systems

Citation: Gintciak, A., Burlutskaya, Z., Zubkova, D., Uspenskiy, M., 2024. The Application of Ontology-Based Game Theory for Decision Support in Sociotechnical Systems. Sustainable Development and Engineering Economics 3, 5. https://doi.org/10.48554/SDEE.2024.3.5

Научная статья
УДК 005.8
DOI: https://doi.org/10.48554/SDEE.2024.3.5

Применение Теории Игр на Основе Онтологии для Поддержки Принятия Решений в Социотехнических Системах

Алексей Гинцяк*, Жанна Бурлуцкая, Дарья Зубкова, Михаил Успенский

Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Российская Федерация, aleksei.gintciak@spbpu.com, zhanna.burlutskaya@spbpu.com, daria.zubkova@spbpu.com, mikhail.uspenskiy@spbpu.com
*Автор, ответственный за переписку: aleksei.gintciak@spbpu.com

Аннотация

В данной работе рассматривается разработка инвариантной онтологии стратегического взаимодействия в социотехнической системе посредством инструментария теории игр. В ходе исследования онтологии рассматриваются как инструмент моделирования социотехнических систем, в том числе инструменты интеграции социальных и технических процессов. Востребованность использования этих инструментов обусловлена необходимостью интеграции человека в техническую систему как равноправного и равноправного элемента, оказывающего как внешнее, так и внутреннее воздействие на систему. Такие социотехнические модели уже применяются для описания информационной структуры предприятий, но в них отсутствует описание принятия решений между элементами системы в рамках стратегического взаимодействия. В рамках решения данной проблемы разрабатывается основанная на онтологии модель социотехнической системы, описывающая взаимодействие как социальных, так и технических элементов посредством игрового взаимодействия. Каждый из участников взаимодействия описывается в терминах теории игр с выделением возможных стратегий и соответствующих выигрышей. Посредством интерактивных сущностей модели теории игр происходит игровое взаимодействие между участником и выбором соответствующих стратегий поведения. Модель представляет собой гибкий масштабируемый инструмент для построения имитационных моделей социотехнических систем. Полученные результаты будут проверены при построении реальных социотехнических систем, а онтология будет дорабатываться в соответствии с полученными результатами.

Ключевые слова: теория игр, цифровизация, онтология, социотехнические системы

Цитирование: Гинцяк, А., Бурлуцкая, Ж., Зубкова, Д., Успенский, М., 2024. Применение Теории Игр на Основе Онтологии для Поддержки Принятия Решений в Социотехнических Системах. Sustainable Development and Engineering Economics 3, 5. https://doi.org/10.48554/SDEE.2024.3.5

1. Introduction

The digitalisation of technical processes has changed approaches to management decision-making (Smirnov, 2021). Emerging technologies for the acquisition and processing of big data enable managers to get all the necessary information about the status, characteristics and functionality of various technical equipment (Dobrinskaya, 2021). The information obtained is processed and then used in digital models to predict the behaviour of technical systems. However, such models do not take into account the impact of the humans who work with technical equipment (Li et al., 2022). Thus, models of isolated technical systems fail to take into account the influence of the external environment. To solve this problem, models of sociotechnical systems are being developed. A sociotechnical system is a complex mixed system incorporating social and technical subsystems and the external environment (Prokopchuk, 2010; Tabachkov et al., 2010). The social system is characterised by human involvement in various processes and interrelations. This system describes the work of various enterprises, corporations, companies and business units (Xue et al., 2023). A technical system is an artificially created system designed to meet a technical need. This system includes various equipment, machines, devices and technologies (Kong et al., 2023).

The scientific community is interested in studying sociotechnical systems since they are pervasive in human societies. A technical system that lacks interaction with a human actor will be unusable since the technical system was initially intended to meet the technical needs of people. Thus, to maintain device or equipment functionality, the involvement of people, that is, a social system, is required (Prokopchuk, 2010).

Simulation modelling is used to model socioeconomic systems since it contains multiple paradigms that satisfy all the properties of these systems. However, the consideration of sociotechnical systems requires the integration of the tools used in the modelling of technical systems, such as mathematical modelling and dynamic prediction, sensitivity analysis, verification, validation and calibration (Gintciak, 2021). Thus, there is a need to develop tools for modelling sociotechnical systems, including tools for the integration of social and technical processes. Integration tools primarily refer to conceptual schemes of interaction between the elements of social and technical systems. Such descriptive models are ontology-based models. Therefore, to model the interaction between technical and social objects, game theory, which allows for the unification of the interaction participants as agents with their own goals and strategies, can be applied. In this interaction, the elements of the social and technical systems are considered equivalent and equal agents striving to achieve maximum efficiency by interacting with each other (Nikitenko et al., 2024).

The purpose of this work is to develop an invariant ontology of strategic interaction in a sociotechnical system in terms of game theory. The study examines game theory tools, taking into account application peculiarities and various types of interactions, and provides an analysis of the application of ontologies in various socioeconomic and sociotechnical systems. As a result of the research, an ontology of a sociotechnical system is developed, taking into account the description of entities and their game interactions. The results of this work can be applied to building models of sociotechnical systems using game theory tools. These solutions provide support for decision-making in sociotechnical systems.

2. Materials and Methods

2.1. Application of Ontologies

An ontology is a formal, explicit specification of a general conceptualisation (Khadir et al., 2021). In a loose sense, an ontology is a description of knowledge. Thus, an ontology-based model is one that describes knowledge. The following types of ontologies are distinguished:

1. Domain ontologies capture knowledge that is valid for a specific type of domain (e.g. electronic, medical, mechanical, or digital domains).

2. Generic ontologies are valid in several spheres. Generic ontologies are also called super theories and core ontologies.

3. Application ontologies contain all the necessary knowledge for modelling a specific domain (usually a combination of domain ontologies and method ontologies).

4. Representational ontologies are not tied to any particular subject area. Such ontologies provide representational entities without specifying what should be represented.

The most common example of using ontology is in knowledge-based systems, that is, systems that use artificial intelligence and exchange knowledge. This communication requires agreement on three levels: the representation language format, an agent–communication protocol, and the content specifications of the transmitted data (knowledge) (Studer et al., 1998). Ontologies are used for the third level: content-specific specifications.

Ontologies are also at the core of semantic networks, since they offer a formal method for defining concepts and the semantic relations between them. This allows for reasoning and the extraction of facts (when a certain level of formality is reached) (Gruber, 1993).

The reason that ontologies are so widely used is because they reflect a common understanding of a certain subject area, which can be transmitted between people and computers as a code (Fayoumi and Williams, 2021).

The use of ontologies for modelling sociotechnical and socioeconomic systems allows for the consideration of people as well as software and hardware as equivalent components (Prokopchuk, 2010). For example, healthcare industry models describe the interaction between patients, the information system and medical staff. Such complex integrated systems, including interaction and information transfer at several levels between agents through technical means, cannot be described by one model and require careful study of the logical bindings within the ontology as the basis of a multi-agent model (Hinkelmann et al., 2016). A comprehensive social engineering ontology is applied in the same way for security analysis in general and social engineering attacks in particular (Li et al., 2022). The ontology is used to describe the connection between social engineering concepts and security concepts. The resulting ontology is formalised via description logic and then used to develop recommendations for technical equipment safety assurance based on behavioural models of social objects. It follows that developing an ontology is the first step in building a digital model of a system by combining artificial intelligence and computing technology (Sahlgren, 2021).

The use of ontologies for modelling sociotechnical systems makes it possible to apply ontologies to describe the integration of social processes and digital technologies. Thus, an ontology is a tool for analysing sociotechnical transitions and environmental sustainability within large socioeconomic and sociotechnical systems (Cuaresma et al., 2022; Rahayu et al., 2022).

The analysed examples of ontology applications consider the interaction of the elements of sociotechnical systems without taking into account their individual goals and characteristics. Thus, the obtained models focus on descriptions of the system structure but do not provide descriptions of the decision-making mechanisms. In this case, finding solutions means selecting strategies for each of the interaction participants, both as living agents and as technical equipment. Thus, game theory is a tool for developing formalised descriptions of strategy selection by various system elements.

2.2. Game Theory

Current game theory methods provide a relevant tool for the interaction of various parties in a game format. They allow for the determination of optimal strategies by game participants, depending on the conditions entered and the initial task. Game theory is applied in economics (Chica et al., 2018), psychology and behavioural sciences (Bhogal et al., 2017; Dixit and Nailbuff, 2015; Wang et al., 2019), computer science (Sergeev. 2006), investment (Chica et al., 2018) and biology (Dixit and Nailbuff, 2015).

Game theory is a mathematical description of the conflicts between two or more players, each of which pursues its own goals and personal interests. In this case, a conflict is a clash between the interests of several parties. The personal interests of the players determine their objective function, which is the basis of a player's strategy set. At the same time, a strategy is a possible set of players' actions. It is important to note that there may be uncertainty in the behaviour of the parties, but the rules of the game are always defined and known to all players. As a result of the interaction, the parties receive their winnings, which determine the outcome of the game (Babakina and Obiremko, 2019; Wang et al., 2019).

Game theory is divided into several types of interactions, as follows:

1. Cooperative and noncooperative (Chalkiadakis, 2011): Cooperative games differ from noncooperative ones in that they offer the possibility of joining coalitions. Another significant difference lies in the objects of research. In noncooperative games, each player acts only in the area of their interests. In this case, the noncooperative game solution is the Nash equilibrium (Williams, 2017). A Nash equilibrium is a set of players' strategies in which they cannot improve their outcome. In the event that a player has no motivation to change the chosen strategy profile, since the change will not increase the player's winnings, and the other participants adhere to their chosen strategy, then this profile is a Nash equilibrium (Chica et al., 2018). Thus, in noncooperative games, the player is an individual, while in cooperative games, the player is a coalition (a group of participants).

2. Symmetric and asymmetric (Wang et al., 2019): The game is considered symmetric if the players have the same strategies. An asymmetric game is one in which the strategies of the players diverge, so the outcome of the game differs, as well.

3. Zero-sum and non-zero-sum (Bailey and Piliouras, 2019): In zero-sum games, there is no opportunity to increase or decrease the game's resources. In this case, the winnings are equal to the total loss. In non-zero-sum games, one player's win does not necessarily imply another player's loss. The total result of such a game can be greater or less than zero.

4. Simultaneous and sequential (Brihaye et al., 2017; Wright and Leyton-Brown, 2017): Simultaneous games imply that all players perform their actions instantly, parallel to each other, and without knowing the actions of their opponents. In sequential games, participants can make moves based on their knowledge of their opponents' previous actions. Actions are performed either in a pre-established or a random order.

5. With complete or incomplete information (Vartanov and Ivin, 2020): In the case of complete information given, the players are informed of the possible strategies of the participants and know all the previous moves of their opponents. Otherwise, the game is called a game with incomplete or partial information.

6. Discrete and continuous (Vartanov and Ivin, 2020; Wang et al., 2019): Discrete games are those with a limited number of events and outcomes, while continuous games last an infinite amount of time.

Depending on the players' personal characteristics and the game features, a game interaction model is selected. Within the present research, an ontological model is developed. It is a descriptive model of the strategic interaction of sociotechnical system elements via game theory tools. The game interaction within the model will be described in terms of game theory and will be a basic type of game with two participants.

3. Results

The developed ontology of the sociotechnical system in terms of game theory has two main levels:

1. The level of system elements description, at which a real strategic interaction is set.

2. The level of the game-theoretic model description, at which a game theory model describing the real interaction is formalised.

The model can also be divided into the following entities:

1. System entities that include strategic interaction (the level of strategic interaction description) and a game theory model (the level of game interaction description).

2. Each agent's individual characteristic entities, including participants (actors) and their goals (the level of strategic interaction description) and these participants' agents with a description of their objective function, set of strategies, and winnings (the level of game interaction description).

3. Interactive entities of the game theory model, including the profile of the agents' strategies and the profile of their winnings (all related to the level of interaction description).

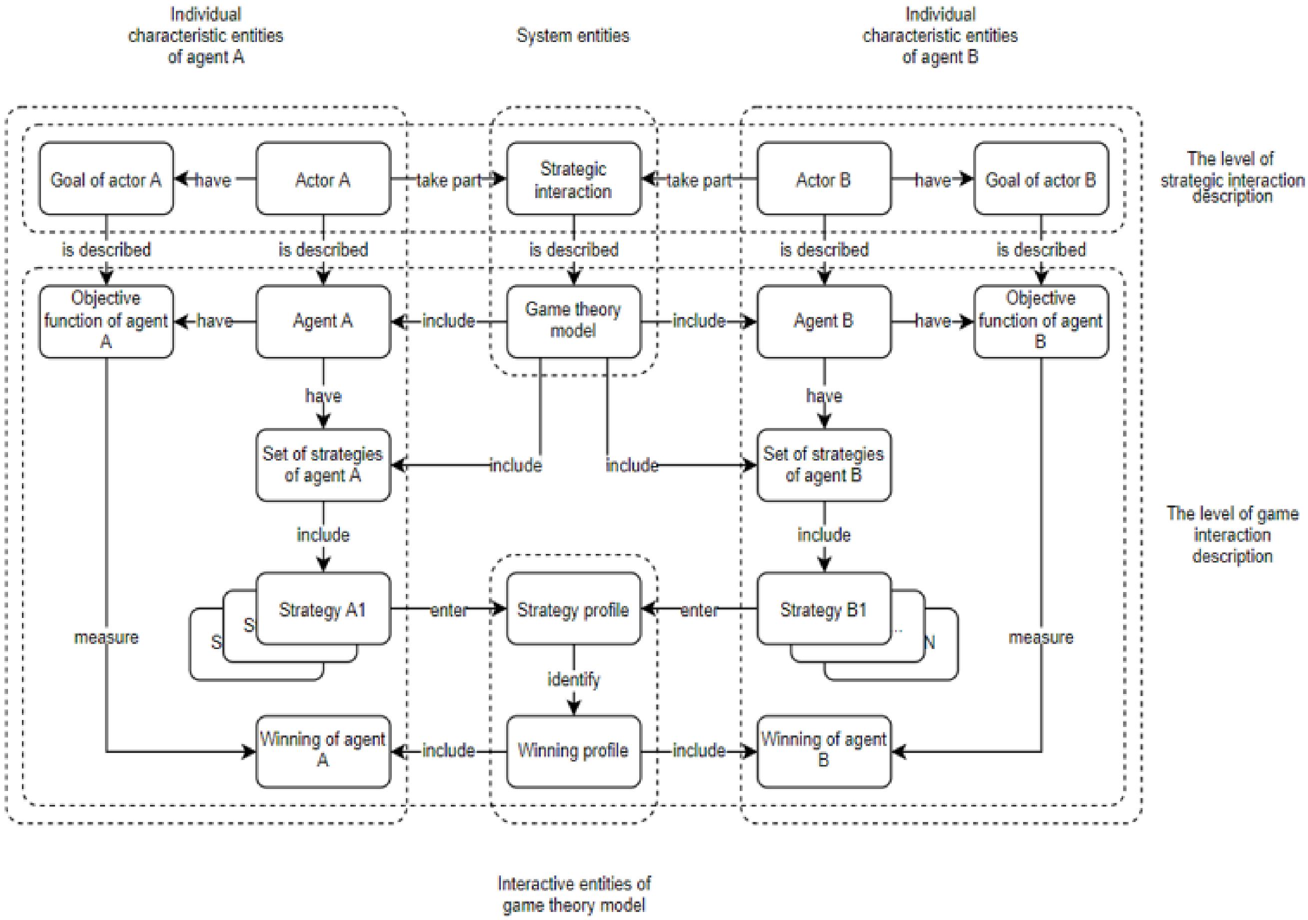

Figure 1. Ontology of the Sociotechnical System

Consider the interconnections between elements at the entity level. Since the purpose of the ontology is to describe the interaction between the participants, the main interaction occurs between them through various elements. It is worth noting that in terms of the sociotechnical system description, both people and technical equipment can act as participants. Their strategies will depend on the objective functions specified in the design and the performance characteristics of the software/device according to its functionality, operation specifications, and other features.

The interaction between the participants is described as a strategic interaction in which they both take part. During the formalisation of strategic interaction as game interaction, each of the participants becomes an element of the game theory model and moves to the level of describing interaction as agents. Within the game theory model, each participant has a set of formalised strategies according to the initial characteristics of the participants. As part of the game interaction, the strategies of both participants are combined into a strategy profile, which determines the winning profile. Then, the winnings of each participant are distributed, and the participants are evaluated according to the objective function of each agent.

It is also worth considering the relationships within entities that describe the agents' individual characteristics. Each agent is an element of the game theory model and is described by the participant's characteristics. Each agent has its own objective function, which is formed according to the purpose of the interaction participant. Each agent has a set of strategies described in terms of game theory. Then, each agent strategy enters the external entity of the model for pairwise formation of game inter-action strategy profiles. According to the interaction results, information about the participant's winnings is received, which is measured in compliance with the objective function.

Applying game theory as a tool for decision-making in sociotechnical systems allows for a description of the strategic interaction between system elements. Describing the strategic interaction of the sociotechnical system's elements via game theory provides additional information about the system necessary for informed management decision-making.

4. Discussion and Conclusions

Ontology-based models of sociotechnical systems have been successfully applied in enterprise information architecture design, where they describe the interconnections between social and technical systems (Rahayu et al., 2022; Sahlgren, 2021). In this case, ontologies represent an important stage in building digital models of enterprises or socioeconomic and sociotechnical systems by combining artificial intelligence with computing technology (Rahayu et al., 2022).

In the present research, an invariant ontology of strategic interaction in a sociotechnical system is developed using game theory. Ontology has been considered a tool for modelling sociotechnical systems, including tools to integrate social and technical processes based on existing examples of ontology applications. In the current study, game theory is used as a tool for the mathematical formalisation of various agents' strategic interactions, taking into account their individual characteristics and goals. The resulting ontology-based model considers the interaction of two agents through system and interactive entities of the game theory model. The ontology describes in detail the individual characteristic entities of each agent from the description of participants and their goals to a set of strategies and winnings. The model is a flexible and scalable tool for building simulation models of sociotechnical systems. The results obtained will be tested when real sociotechnical systems are built, and the ontology will be refined according to the results obtained.

Acknowledgements

The research is funded by the Ministry of Science and Higher Education of the Russian Federation (contract No. 075-03-2024-004 dated 17.01.2024).

References

Babakina, E. P., Obiremko, S. I., 2019. Game theory as one of the effective tools of strategic thinking of managers. Intern. Res. J. 7-1(85), 98–101. https://doi.org/10.23670/IRJ.2019.85.7.019

Bailey, J. P., Piliouras, G., 2018. Multiplicative weights update in zero-sum games. Proceedings of the 2018 ACM Conference on Economics and Computation, 321–338. https://doi.org/10.1145/3219166.321923

Bhogal, M.S., Galbraith, N., Manktelow, K., 2017. Physical attractiveness, altruism and cooperation in an ultimatum game. Curr. Psychol. 3(36), 549–555. https://doi.org/10.1007/s12144-016-9443-1

Brihaye, T. et al., 2017. Dynamics and coalitions in sequential games. Electron. Proc. Theor. Comput. Sci. 256, 136–150. https://doi.org/10.48550/arXiv.1709.02100

Chalkiadakis, G., Elkind, E., Woolridge, M. 2011. Computational aspects of cooperative game theory (Synthesis Lectures on Artificial Intelligence and Machine Learning). Morgan & Claypool, Princeton, NJ. https://doi.org/10.2200/S00355ED1V01Y201107AIM016

Chica, M. et al., 2018. A networked-player trust game and its evolutionary dynamics. IEEE Trans. Evol. Comput. 22(6), 866–878. https://doi.org/10.1109/TEVC.2017.2769081

Cuaresma D. C. N. et al., 2022. Optimal strategies and cost-benefit analysis of the n-player weightlifting game. Sci. Rep. 12(1), 8482. https://doi.org/10.1038/s41598-022-12394-z

Dixit, A., Nailbuff, B., 2015. Game theory: The art of strategic thinking in business and life. Mann, Ivanov and Ferber.

Dobrinskaya, D.E., 2021. What is a digital society? Soc. Sci. Tech. 12(2), 112–129. https://doi.org/10.24412/2079-0910-2021-2-112-129
Fayoumi, A., Williams, R., 2021. An integrated socio-technical enterprise modelling: A scenario of healthcare system analysis and design. J. Ind. Inf. Integr. 23, 100221. https://doi.org/10.1016/j.jii.2021.100221
Gintciak, A.M. 2021. Classification of game-theoretic models in project management: Literary review. Appl. Math. Control Sc. 3, 130–153. https://doi.org/10.15593/2499-9873/2021.03.07
Gruber, T.R., 1993. A translation approach to portable ontology specifications. J. Knowl. Acquis. 5(2), 199–220. https://doi.org/10.1006/knac.1993.1008
Hinkelmann, K et al., 2016. A new paradigm for the continuous alignment of business and IT: Combining enterprise architecture modelling and enterprise ontology. Comput. Ind. 79, 77–86. https://doi.org/10.1016/j.compind.2015.07.009
Khadir, A. C., Aliane, H., Guessoum, A., 2021. Ontology learning: Grand tour and challenges. Comput. Sci. Rev. 39, 100339. https://doi.org/10.1016/j.cosrev.2020.100339
Kong, F., Lu, Z., Kong, L., Chen, T., 2023. Information field in a manufacturing system: Concepts, measurements and applications. Adv. Eng. Inform., 56, 101946. https://doi.org/10.1016/j.aei.2023.101946
Li, T., Wang, X., Ni, Y., 2022. Aligning social concerns with information system security: A fundamental ontology for social engineering. Inf. Syst. 104, 101699. https://doi.org/10.1016/j.is.2020.101699
Nikitenko, V. et al., 2024. Philosophical reflection on artificial intelligence and its impact on the development of society, human, and education. Humanit. 19(9), 67. https://doi.org/10.32782/hst-2024-19-96-07
Prokopchuk, G. A., 2010. The role of innovative sociotechnical systems in the transition to sustainable development (philosophical aspects). Abstract of the dissertation on philosophy, specialty of the Higher Attestation Commission of the Russian Federation 9(8).
Rahayu, N. W., Ferdiana, R., Kusumawardani, S. S., 2022. A systematic review of ontology use in E-learning recommender system. Comp. Edu.: Artif. Intell. 3, 100047. https://doi.org/10.1016/j.caeai.2022.100047
Sahlgren, Otto., 2021. Towards a conception of sociotechnical pathology. Proceedings of the Conference on Technology Ethics 2021, 48–62.
Sergeev, A.M., 2006. Game theory and economic institutions. J. Econ. Theory 1, 88–105.
Smirnov, A.V., 2021. Digital society: Theoretical model and Russian reality. Monitor. Pub. Opin: Econ. Social Changes 1, 129–153. https://doi.org/10.14515/monitoring.2021.1.1790
Studer, R., Benjamins, V., Fensel, D., 1998. Knowledge engineering: Principles and methods. Data Knowl. Eng. 25(1–2), 161–197. https://doi.org/10.1016/S0169-023X(97)00056-6
Tabachkov, E. R., Savinovskikh, A. G., Cherny, V. I., 2010. Socio-technical system, its place and role in society. Soc. Power, 1, 20–23.
Vartanov, S. A., Ivin, E. A., 2020. Applied Game Theory for Economists.
Wang, W. et al., 2019. A survey on consensus mechanisms and mining strategy management in blockchain networks. IEEE Access 7, 22328–22370. https://doi.org/10.1109/ACCESS.2019.2896108
Williams, J.D., 2017. The perfect strategist, or a primer on the theory of strategic games. Librocom, Moscow, 274.
Wright, J.R., Leyton-Brown, K., 2017. Predicting human behavior in unrepeated, simultaneous-move games. Games Econ. Behav. 106, 16–37. https://doi.org/10.1016/j.geb.2017.09.009
Xue, X. et al., 2023. Computational experiments: A new analysis method for cyber-physical-social systems. IEEE Trans. Syst. Man Cybern. Syst. 54(2), 813–826. https://doi.org/10.1109/TSMC.2023.3322402.

Список источников

Babakina, E. P., Obiremko, S. I., 2019. Game theory as one of the effective tools of strategic thinking of managers. Intern. Res. J. 7-1(85), 98–101. https://doi.org/10.23670/IRJ.2019.85.7.019
Bailey, J. P., Piliouras, G., 2018. Multiplicative weights update in zero-sum games. Proceedings of the 2018 ACM Conference on Economics and Computation, 321–338. https://doi.org/10.1145/3219166.321923
Bhogal, M.S., Galbraith, N., Manktelow, K., 2017. Physical attractiveness, altruism and cooperation in an ultimatum game. Curr. Psychol. 3(36), 549–555. https://doi.org/10.1007/s12144-016-9443-1
Brihaye, T. et al., 2017. Dynamics and coalitions in sequential games. Electron. Proc. Theor. Comput. Sci. 256, 136–150. https://doi.org/10.48550/arXiv.1709.02100
Chalkiadakis, G., Elkind, E., Woolridge, M. 2011. Computational aspects of cooperative game theory (Synthesis Lectures on Artificial Intelligence and Machine Learning). Morgan & Claypool, Princeton, NJ. https://doi.org/10.2200/S00355ED1V01Y201107AIM016
Chica, M. et al., 2018. A networked-player trust game and its evolutionary dynamics. IEEE Trans. Evol. Comput. 22(6), 866–878. https://doi.org/10.1109/TEVC.2017.2769081
Cuaresma D. C. N. et al., 2022. Optimal strategies and cost-benefit analysis of the n-player weightlifting game. Sci. Rep. 12(1), 8482. https://doi.org/10.1038/s41598-022-12394-z
Dixit, A., Nailbuff, B., 2015. Game theory: The art of strategic thinking in business and life. Mann, Ivanov and Ferber.
Dobrinskaya, D.E., 2021. What is a digital society? Soc. Sci. Tech. 12(2), 112–129. https://doi.org/10.24412/2079-0910-2021-2-112-129
Fayoumi, A., Williams, R., 2021. An integrated socio-technical enterprise modelling: A scenario of healthcare system analysis and design. J. Ind. Inf. Integr. 23, 100221. https://doi.org/10.1016/j.jii.2021.100221
Gintciak, A.M. 2021. Classification of game-theoretic models in project management: Literary review. Appl. Math. Control Sc. 3, 130–153. https://doi.org/10.15593/2499-9873/2021.03.07
Gruber, T.R., 1993. A translation approach to portable ontology specifications. J. Knowl. Acquis. 5(2), 199–220. https://doi.org/10.1006/knac.1993.1008
Hinkelmann, K et al., 2016. A new paradigm for the continuous alignment of business and IT: Combining enterprise architecture modelling and enterprise ontology. Comput. Ind. 79, 77–86. https://doi.org/10.1016/j.compind.2015.07.009
Khadir, A. C., Aliane, H., Guessoum, A., 2021. Ontology learning: Grand tour and challenges. Comput. Sci. Rev. 39, 100339. https://doi.org/10.1016/j.cosrev.2020.100339
Kong, F., Lu, Z., Kong, L., Chen, T., 2023. Information field in a manufacturing system: Concepts, measurements and applications. Adv. Eng. Inform., 56, 101946. https://doi.org/10.1016/j.aei.2023.101946
Li, T., Wang, X., Ni, Y., 2022. Aligning social concerns with information system security: A fundamental ontology for social engineering. Inf. Syst. 104, 101699. https://doi.org/10.1016/j.is.2020.101699

Nikitenko, V. et al., 2024. Philosophical reflection on artificial intelligence and its impact on the development of society, human, and education. Humanit. 19(9), 67. https://doi.org/10.32782/hst-2024-19-96-07

Prokopchuk, G. A., 2010. The role of innovative sociotechnical systems in the transition to sustainable development (philosophical aspects). Abstract of the dissertation on philosophy, specialty of the Higher Attestation Commission of the Russian Federation 9(8).

Rahayu, N. W., Ferdiana, R., Kusumawardani, S. S., 2022. A systematic review of ontology use in E-learning recommender system. Comp. Edu.: Artif. Intell. 3, 100047. https://doi.org/10.1016/j.caeai.2022.100047

Sahlgren, Otto., 2021. Towards a conception of sociotechnical pathology. Proceedings of the Conference on Technology Ethics 2021, 48–62.

Sergeev, A.M., 2006. Game theory and economic institutions. J. Econ. Theory 1, 88–105.

Smirnov, A.V., 2021. Digital society: Theoretical model and Russian reality. Monitor. Pub. Opin: Econ. Social Changes 1, 129–153. https://doi.org/10.14515/monitoring.2021.1.1790

Studer, R., Benjamins, V., Fensel, D., 1998. Knowledge engineering: Principles and methods. Data Knowl. Eng. 25(1–2), 161–197. https://doi.org/10.1016/S0169-023X(97)00056-6

Tabachkov, E. R., Savinovskikh, A. G., Cherny, V. I., 2010. Socio-technical system, its place and role in society. Soc. Power, 1, 20–23.

Vartanov, S. A., Ivin, E. A., 2020. Applied Game Theory for Economists.

Wang, W. et al., 2019. A survey on consensus mechanisms and mining strategy management in blockchain networks. IEEE Access 7, 22328–22370. https://doi.org/10.1109/ACCESS.2019.2896108

Williams, J.D., 2017. The perfect strategist, or a primer on the theory of strategic games. Librocom, Moscow, 274.

Wright, J.R., Leyton-Brown, K., 2017. Predicting human behavior in unrepeated, simultaneous-move games. Games Econ. Behav. 106, 16–37. https://doi.org/10.1016/j.geb.2017.09.009

Xue, X. et al., 2023. Computational experiments: A new analysis method for cyber-physical-social systems. IEEE Trans. Syst. Man Cybern. Syst. 54(2), 813–826. https://doi.org/10.1109/TSMC.2023.3322402.

The article was submitted 12.09.2024, approved after reviewing 25.09.2024, accepted for publication 07.10.2024.

Статья поступила в редакцию 12.09.2024, одобрена после рецензирования 25.09.2024, принята к публикации 07.10.2024.

About authors:

1. Aleksei Gintciak, Ph.D in technology, head of Laboratory of Digital modeling of Industrial systems, Peter the Great St. Petersburg Polytechnic University, Saint Petersburg, Russian Federation. aleksei.gintciak@spbpu.com, https://orcid.org/0000-0002-9703-5079.

2. Zhanna Burlutskaya, Junior Researcher of Laboratory of Digital modeling of Industrial systems, Peter the Great St. Petersburg Polytechnic University, Saint Petersburg, Russian Federation. zhanna.burlutskaya@spbpu.com, https://orcid.org/0000-0002-5680-1937

3. Darya Zubkova, Junior researcher in Laboratory of Digital modeling of Industrial systems, Peter the Great St. Petersburg Polytechnic University, Saint Petersburg, Russian Federation. daria.zubkova@spbpu.com, https://orcid.org/0000-0003-1106-5080

4. Mikhail Uspenskiy, Ph.D in technology, Senior Researcher in Laboratory of Digital modeling of Industrial systems, Peter the Great St. Petersburg Polytechnic University, Russian Federation. mikhail.uspenskiy@spbpu.com, https://orcid.org/0000-0003-3417-7376

Информация об авторах:

1. Алексей Гинцяк, кандидат технических наук, заведующий лабораторией «Цифровое моделирование индустриальных систем», Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Российская Федерация. aleksei.gintciak@spbpu.com, https://orcid.org/0000-0002-9703-5079

2. Жанна Бурлуцкая, младший научный сотрудник лаборатории «Цифровое моделирование индустриальных систем», Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Российская Федерация. zhanna.burlutskaya@spbpu.com, https://orcid.org/0000-0002-5680-1937

3. Дарья Зубкова, младший научный сотрудник лаборатории «Цифровое моделирование индустриальных систем», Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Российская Федерация. daria.zubkova@spbpu.com, https://orcid.org/0000-0003-1106-5080

4. Михаил Успенский, кандидат технических наук, ведущий научный сотрудник лаборатории «Цифровое моделирование индустриальных систем», Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Российская Федерация. mikhail.uspenskiy@spbpu.com, https://orcid.org/0000-0003-3417-7376