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Society 5.0: Human-Centered Society Challenges and Solutions

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Preface

This book focuses on open issues of Society 5.0, a new paradigm of a society, that balances a human-centered approach and technologies based on cyber-physics systems and artificial intelligence. The book contains results of how intelligent or cyber-physical systems help to improve the quality of life in society despite new challenges.

This book includes five sections. Section Society 5.0: Biomedicine and Healthcare present how cyber-physical systems help in healthcare, e.g., personal assessment (human functional state assessment), rehabilitation of children with obesity, breast cancer diagnostics, healthy diet design and others. In the chapter, the problem of data gathering and transmission is considered. The second Section, Society 5.0: Innovations in Socio-Economic Systems highlight new findings on open socio-economic systems, protection of intellectual property using VR/AR techniques, analysis of innovative competitiveness of regions, multi-level management of organizational systems. Society 5.0: Intelligent Energetics includes chapters concerning the life cycle control of electric grid equipment via digital twin of the main and auxiliary equipment, enhancing of power grid company management, approaches of energy consumption analysis and new results for vortex type wind-driven power plant.

A section, Society 5.0: Advances in Transport Systems, provides new results on intellectual transport design and management. The last section, Society 5.0: Human-centric technologies consider interoperability issues, the communication of human and machines as well as designers and engineers of cyber-physical systems.

This book is directed to researchers, practitioners, engineers, software developers, professors, and students. We do hope the book will be useful for them.

The edition of the book is dedicated to 2021, the Year of Science and Technology in Russia and technically supported by the Project Laboratory of Cyber-Physical Systems of Volgograd State Technical University.

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Contents

Society 5.0: Biomedicine and Healthcare

Substantiation of the Result of the Work of the Cyber-Physical System for Breast Cancer Diagnostics

Ilya Germashev, Victoria Dubovskaya, and Alexander Losev

Abstract The chapter is devoted to the method of data analysis and processing in cyber-physical systems for the diagnosis of patients in medicine. In particular, the approach to processing the results of the thermometric data analysis system is discussed. In this work, the influence of cancer signs on the diagnosis made after the work of the classifier is studied. The influence of each sign on both the correctness and the error of the diagnosis is determined. The initial set of highly informative diagnostic thermometric signs used in classification algorithms was previously obtained by A. G. Losev and V. V. Levshinsky. In this chapter, the next stage of building a modern medical cyber-physical system is considered. This stage is the development of a mechanism for justifying the obtained diagnostic solution in a language that is understandable to the doctor. A factor model is constructed for compiling a hierarchy of signs used to justify the classification result. Further directions of research based on the obtained knowledge are proposed, in particular, the use of the fuzzy inference mechanism to decide the strengthening or weakening of signs in the model.

Keywords Cyber-physical systems · Microwave thermometry · Breast cancer · Parameter monitoring · Factor analysis

1 Introduction

The integration of artificial intelligence methods as well as mathematical modeling in medicine is one of the most important modern trends in world health care [1–5]. A special place is occupied by classification methods in diagnostics. Several works

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[5–11] demonstrate a significant increase in the accuracy of disease detection in cases when the above methods are applied to medical data.

To automate the process of collecting data on the patient's condition, processing in real-time, as well as managing the condition, in medical practice, a computer is used in combination with measuring and control equipment. Medical cyber-physical systems have made it possible to raise instrumental research methods and intensive care to a new qualitative level.

Early detection of breast cancer has been one of the key problems in medical diagnostics over the past decades. According to the WHO, the urgency of this task is due to the rejuvenation of cancer (the incidence of breast cancer in women from 19 to 39 years old increased by 34%), and an increase in the proportion of sick patients by 1–2% per year. At the same time, doctors in most cases find stage III-IV cancer, in which a complete cure is unlikely. In patients over 40 years of age, pathological conditions of the mammary glands are diagnosed in 60% of cases.

The high frequency of detection of already advanced forms of the disease is due to the untimely treatment of patients and the lack of effective methods for diagnosing the early stages of breast cancer. Traditional examination methods (palpation, mammography, cytology, etc.) do not solve the problem of early detection of breast cancer. To increase the survival rate, specialists are turning their attention to new methods, due to which it is possible to study thermophysiology.

Among the promising methods of early diagnosis, capable of recognizing the disease before structural changes in the organ, the method of microwave radiothermometry stands out [12–16]. Since its inception, mammalogy has been the main area of application of the RTM method. This method is based on measuring the intrinsic electromagnetic radiation of human tissues in the microwave and infrared range. Its distinguishing characteristics are the safety of the patient's health and the availability of mass screening. Safety plays a key role, as recently benign breast tumors are detected in every 4 women under the age of 30 years.

The analysis of foreign and Russian literature, which is devoted to radiothermographic medical equipment, allows us to draw the following conclusion: at the moment, many fundamental issues of the technology for creating highly informative receivers of thermal electromagnetic radiation in the context of medical and biological problems have been solved. Currently, in many areas of practical medicine, the diagnostic capabilities of this method are being studied in various ranges of wavelengths [13].

For the examination, a software and hardware complex are used, designed for screening patients, analyzing the data obtained, and conducting classification. The proposed cyber-physical system consists of a data collection module, an intelligent data processing module, and a module for interpreting processed data. This structure is quite common in such systems aimed at analyzing medical data and indicators (see, for example, [17]).

Measurements are carried out using antenna applicators. They are installed on the surface of the patient's body. The measuring system registers electromagnetic radiation, which is proportional to the radio brightness. The temperature is related to the physical temperature of the tissues and the degree of absorption of electromagnetic waves in them. Different antenna applicators have their characteristics.

The sensors record the temperature of the breast in the IR and RTM range, which is used for further analysis of the patient's condition.

However, the complexity of the data obtained using the RTM-complex leads to a narrowing of the method's scope and leveling of its unique capabilities. The multiplicity of perception and analysis of data obtained using microwave thermometry, which arises among doctors without special training, necessitates the creation of cyber-physical diagnostic systems. For such systems, it is important to take into account the subtle classifications and complex interrelationships of signs, which specialists pay attention to in explicit and implicit form during diagnostics and forecasting.

The path of development is the transition from formalizations that reflect the solution option that corresponds to the logic of the doctor in the training version, to the ability to extract and formalize difficult-to-verbalize representations.

2 Formulation of the Problem

An important aspect of creating intelligent systems for analyzing high-dimensional data is the development of mathematical models for constructing optimal feature subspaces. The analysis of the classification algorithms developed in this area shows that the use of temperature data obtained as a result of the survey as a feature space does not provide the necessary diagnostic accuracy and the efficiency of the decision justification block. Significantly higher results are shown by the use of feature spaces built based on the corresponding descriptive and physical and mathematical models [6–8, 18, 19].

At the same time, effective methods and algorithms for intelligent analysis of thermometric data do not guarantee reliable detection of the disease. The classification accuracy is determined not only by the set of features used but also by their qualitative parameters. For most biomedical problems, the influence of each sign on the erroneousness or correctness of the classification results plays an important role. Also, modern requirements for medical cyber-physical systems need a mechanism to substantiate the obtained diagnostic solution in a natural language, understandable to a specialist. The construction of the hierarchy of signs used in this case is also impossible without assessing the level of confidence in a particular sign when making a diagnosis.

The task of determining the influence on the classification result can be solved using regression analysis. However, some limitations are imposed on this method. Thus, difficulties arise when trying to obtain estimates of the impact on the classification efficiency of a large number of signs. To avoid such a contradiction, in this study, it is proposed to use the multidimensional statistical method. The factor analysis is based on the identification, through the analysis of variations in variables and their correlations, of not directly observable and not measurable characteristics–common factors.

The prospects of using statistical methods in the development of complex analysis systems in the field of medicine are also noted in [20].

3 Mathematical Model

The data used in this study was provided by many Russian and Slovenian cancer centers. Sample H represents information about patients and consists of n elements. ($n = 15{,}176$). This sample is divided into two groups: the first includes 13,570 elements with the label "Healthy" in the diagnosis field and 1546 elements with the label "Cancer". The first set is denoted by H_0, the second by H_1, note that $H = H_0 \cup H_1$.

Elements of the corresponding sets are denoted as $h_{i_k} \in H_k, i_k = 1, \ldots, n_k$, where $k = 0{,}1$ labels "Healthy", "Cancer", respectively, $n_0 + n_1 = n$.

Note that according to the existing method of examining patients using the RTM-complex, temperature measurements begin from two points in the center of the chest. This was followed by 10 points of the right and left glands and the axillary region. The measurement scheme is shown in Fig. 1.

Thus, 44 temperatures are obtained in the RTM range (internal) and the IR range (skin). The sample of temperature data can be represented in the form of a matrix:

$$S = \left(T_0^1 \cdots T_{43}^1 \vdots \ddots \vdots T_0^k \cdots T_{43}^k T_0^{k+1} \cdots T_{43}^{k+1} \vdots \ddots \vdots T_0^n \cdots T_{43}^n \right),$$

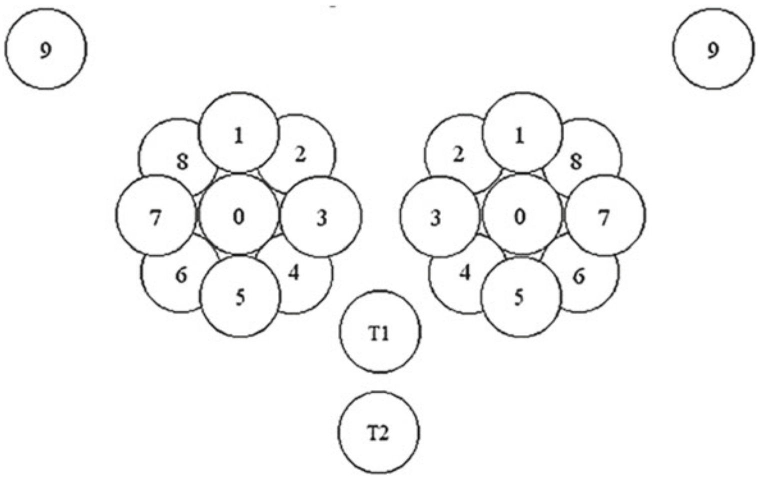

Fig. 1 Breast measurement points (0–8), including axillary point (9). Points T1 and T2 are used as reference points

where T_i^j, i = 0, …, 9—temperatures of the i-th point of the right breast of the j-th patient (RTM-range);

T_i^j, i = 10, …, 19—temperature of the [i–10] point of the right breast of the j-th patient (IR-range);

T_i^j, i = 20, …, 29—temperature of the [i–20] point of the left breast of the j-th patient (RTM-range);

T_i^j, i = 30, …, 39—temperature of the [i–30] point of the left breast of the j-th patient (IR-range);

$T_{40}^j = T1$, $T_{41}^j = T2$—temperatures of the reference points of the j-th patient (RTM-range);

$T_{42}^j = T1$, $T_{43}^j = T2$—temperatures of the reference points of the j-th patient (IR-range).

The patient card also contains the data that is collected by the specialist before the start of the examination. There is age, ambient temperature, breast diameter, day of the cycle, height, and weight of the patient among them.

All these data together with the temperature data matrix S are included in the matrix X = {x_{ij}} of the initial data, i = 1, …, n, j = 1, …, m. Thus, the measured parameters x_{ij}, i = 1, …, n, j = 1, …, m can be real or integer.

The feature space used in the patient classification problem consisted of elements representing quantitative characteristics of the asymmetry of the temperature fields of the mammary glands, the ratio of skin and internal temperatures, temperature spread, breast temperature oscillations, and other parameters of the qualitative description of the nuances of the behavior of the temperature fields of patients of different diagnostic classes. The basis for the construction of these signs is descriptive mathematical models of temperature glands.

In this case, a set of norms and seminorms of some functional spaces is applied, which represent a mathematical formalization of well-known heuristics. To approximate them, an appropriate set of real-valued functions is used, depending on the range (RTM or IR) and temperature measurement points. Based on the matrix X, the values of the signs are calculated, which describe various aspects of the behavior of the temperature field $p_{ir} = g_r(x_{i1}, \ldots, x_{im}), r = 1, \ldots, s$, where g_r is a real-valued function. The process of constructing such functions is described in detail in [3].

The result of the classification is represented by the value 0, if the diagnosis is "Healthy", 1—the diagnosis is ""Cancer", thus the diagnosis $\alpha_i = M(p_{i1}, \ldots, p_{is}) \in \{0, 1\}$. Here, M denotes the classification method.

As a result of the classification algorithm, a sample is obtained that can be divided into two parts. First, this is H^0, consisting of 2766 elements, represents the data of the mammary glands, for which the algorithm makes an erroneous classification (the diagnosis is made incorrectly). Secondly, this is H^1, consisting of 12,350 elements,—the data of the mammary glands, for which the classification algorithm determines the correct diagnosis. Moreover, $H = H^0 \cup H^1$, $H^0 \cap H^1 = \varnothing$. The sensitivity of the algorithm used is 0.81, and the specificity is 0.68.

As mentioned in the previous section, the diagnosis is influenced by the signs used in the classification process. To solve the problem of determining the level of influence p_r on the error *(l = 0)* / correctness *(l = 1)* of the classification, the factors F_r^l can be determined:

$$F_r^l = c_{r1}^l p_{1r} + c_{r2}^l p_{2r} + \cdots + c_{rs}^l p_{sr},$$

where $r = 1, \ldots, s; l = 0, 1$.

4 Computational Experiment and Its Discussion

The model of factor analysis of signs is built using the Statistica package. At the first stage, normalization is applied to the initial data, which are represented by a matrix of values. Then, the principal component method (see, for example, [21]) is used for each sample in turn to obtain factor loadings.

This method is based on determining the minimum number of factors that make the greatest contribution to the variance of the data. In most cases, the total variance of the variables is decomposed in such a way that the first K components explain a large proportion of the variance, and the contribution of the rest is minimal. After getting information about how much variance each factor is explained, it is possible to consider the optimal number of factors.

According to Table 1, twelve components have an eigenvalue greater than 1. The first principal component accounts for 27.49% of the total variance, the first two for 42.64%, and so on. In this case, when deciding on the number of factors that should be left for further analysis, formal criteria or Kaiser criterion is used. As a result, twelve factors are selected that explain 85.44% of the total variance. Thus, factors that do not have a significant contribution to the variance, which is a value within the variance of a single variable, are omitted.

The method used allowed us to obtain a matrix of components, a fragment of which is presented in Table 2 (the values are given only for the first 9 components).

Table 1 Explained cumulative variance

	Extraction sums of squared loadings		
	Total	% Variance	Total %
K_1	16.77	27.49	27.49
K_2	9.24	15.15	42.64
K_3	5.13	8.42	51.05
K_4	4.56	7.48	58.54
K_5	4.06	6.66	65.20
K_6	2.95	4.84	70.04
K_7	2.36	3.87	73.91

Table 2 Component matrix (sample H^0)

Sign	Components								
	K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8	K_9
MG001	0.1	0.84	0.15	0.03	0.10	0.29	0.01	−0.12	0.20
MG002	0.16	0.8	0.16	0.01	0.12	0.29	−0.01	−0.11	0.15
MG003	0.24	0.81	0.17	−0.02	0.16	0.23	−0.03	−0.08	0.03
MG004	0.57	0.58	0.16	0.01	0.12	0.21	−0.03	−0.04	−0.03
MG005	0.53	0.04	−0.4	−0.46	−0.01	−0.02	0.11	0.31	0.28
MG006	0.25	−0.29	0.76	0.33	0.06	−0.06	0.01	−0.20	0.02
MG007	0.34	0.40	0.41	0.35	0.39	−0.35	−0.11	−0.05	−0.19

The interpretation of the given factor loadings allowed us to identify:

1. There are no factor loadings of variables higher than 0.5 in components 7, 8, 9, 11, and 12. Therefore, these factors can be excluded in the further analysis;
2. The first factor K_1 has the greatest load on variables. Among these variables, it can be note signs that belong to qualitative classes that describe the difference between internal and skin temperatures of the mammary glands, the deviation and fluctuation of the breast's temperatures, the asymmetry of skin temperatures at a specific point of the left and right mammary glands (in the Manhattan metric), and the root-mean-square spread of the breast's temperatures.
3. The second factor is loaded with signs that describe the fluctuation and asymmetry of the difference between the internal and skin temperatures of the breast, the third—with signs that determine the magnitude of the internal gradient (the above-mentioned difference) at various points, the fourth—with features that describe the asymmetry of the average temperature values mammary glands, temperature asymmetry in the nipples in the RTM- and IR-range (internal and skin temperatures); the fourth—temperature fluctuations and asymmetry at specific points of the mammary glands.

According to item 1 of the list, it can be noted that the applied Kaiser criterion retains too many factors since for 5 of them there are no high factor loadings in principle. To confirm the possibility of reducing the number of factors in the model, Cattell's criterion is used, also called the "scree" method (Fig. 1), which consists of finding the point where the strongest deceleration of eigenvalues is observed (Fig. 2).

Similar steps are applied when working with the H^1 sample, for which the correct diagnosis is determined. Initially, 12 factors are also selected to explain 86, 94% of the total variance. The final decision on the number of factors for both samples is made after the interpretation of the results. Subsequently, 7 common factors are left out.

Based on the matrix of factor loadings (Table 3), it can be noted that such signs as the difference in internal temperatures of the left and right mammary glands in the Manhattan and Euclidean metrics, the root-mean-square spread of internal temperatures within one the mammary gland, the difference in internal temperatures

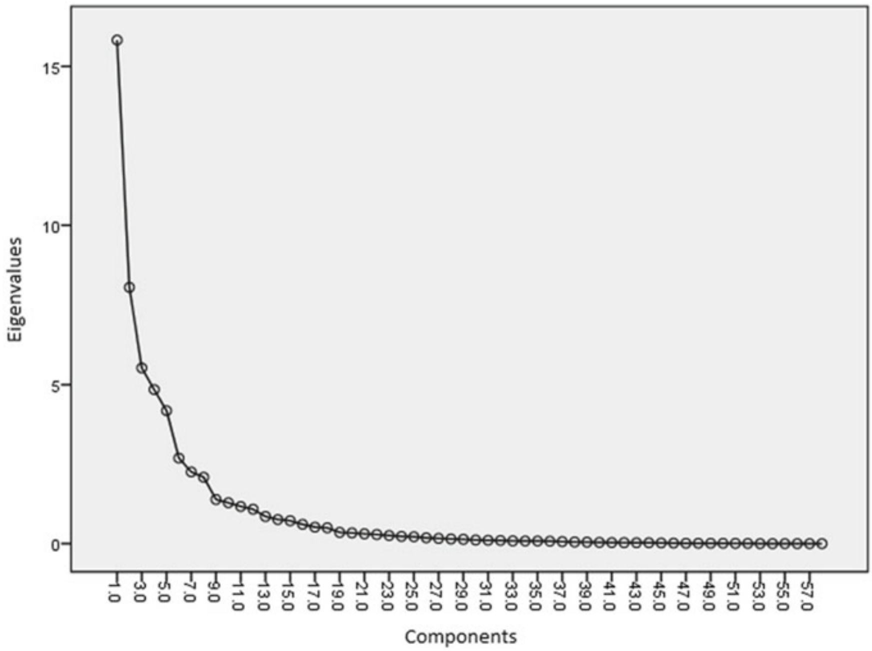

Fig. 2 Scree plot

Table 3 Component matrix (sample H^1)

Sign	Components								
	K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8	K_9
MG001	0.47	−0.11	−0.04	0.54	−0.11	0.24	0.01	0.39	0.09
MG002	0.34	−0.07	−0.04	0.48	−0.12	0.22	0.03	0.38	0.07
MG003	0.45	−0.10	−0.05	0.53	−0.11	0.24	0.01	0.40	0.10
MG004	0.51	−0.10	−0.03	0.55	−0.09	0.23	0.01	0.36	0.10
MG005	0.17	−0.09	−0.10	−0.21	−0.31	0.03	0.56	−0.10	0.01
MG006	−0.06	0.024	−0.02	0.15	0.72	−0.12	−0.28	0.13	0.19
MG007	0.67	−0.40	−0.20	−0.01	0.24	0.02	−0.24	−0.04	−0.03

in the cells, the difference in skin temperatures at specific points of the left and right mammary glands, and the deviation of internal temperatures have high values.

Based on the obtained factor loadings matrices for samples H^0 and H^1 (Tables 2 and 3), the values are obtained, thanks to which it is possible to evaluate the influence of variables on the result of the classifier:

$$c^l_{11} \ldots c^l_{1s} \to c^l_1 \ldots \ddots \ldots c^l_{s1} \ldots c^l_{ss} \to c^l_s,$$

where c_r^l—the level of influence $p_r o$ n the correctness/inaccuracy of the classification.

The value of c_r^l is obtained as a result of rotation using the Varimax method. The selected rotation results in the fact that a large value of the load of the variable corresponds to only one factor, for the other factors the load is very small.

For example, for the sign MG017 (temperature asymmetry in the nipples in the IR-range), the following values are obtained: $c_{17}^0 = 0{,}52$ и $c_{17}^1 = 0{,}67$, for the MG013 (mean square spread of skin temperatures): $c_{13}^0 = 0{,}57$ и $c_{13}^1 = 0{,}63$.

5 Conclusion

Due to the obtained factor loadings assess the level of confidence in a particular sign in the process of making a diagnosis. Taking into account the new knowledge gained, it is possible to build a hierarchy of signs and justify the diagnosis in a language that the doctors understand.

The analysis of the obtained values c_r^l allowed us to divide selected 62 the most informative signs into three groups. The first category includes signs that have high factor loadings for the H^1 sample, where correct diagnoses are made. This may mean that these variables contribute to the fact that the test sample instances are included in the class with the correct results of the classifier. Thus, when justifying the result to specialists, these signs must be taken into account first of all. High factor loadings for the H^0 sample, on the contrary—these signs have an impact on the fact that the classifier makes an incorrect conclusion on the test samples. Thus, based on the results obtained and the existing qualitative classes of signs of the disease, the hierarchy of signs can be presented in the following form:

1. Signs that have a high value of c_r^0:
   a. Thermoasymmetry of the internal temperatures of the left and right mammary glands (in the Euclidean and Manhattan metrics);
   b. Asymmetry of root-mean-square temperature deviations in the RTM- and IR- ranges;
   c. The asymmetry of internal gradients at different points of the mammary glands;
   d. The value of the temperature difference of the axillary region;
   e. The value of the temperature difference and the internal gradient of the nipple;
2. Signs that have a high value of c_r^0:
   a. Thermosymmetry of skin temperatures of the left and right mammary glands (in the Euclidean and Manhattan metrics);
   b. Asymmetry of mean values of breast's temperatures;
   c. The value of the internal gradient at a particular point;

d. The value of the difference between the temperature of the nipple and the average value in the mammary glands;
e. Deviation of the internal temperature gradient from the internal gradient at the 1st and 2nd reference points.

The third group includes 32 signs that affect both the correctness and the error of the result. To decide on the location in the hierarchy of signs for which values c_r^1 И c_r^0 are large, it is proposed to use the fuzzy inference mechanism in further studies for example in [22]. This approach is considered a potential opportunity to increase the efficiency of the classification algorithm. Signs that have high indicators can be enhanced in classification models. It should be noted that the predominant number of these signs characterizes the behavior of temperature fields in the RTM-range. It is necessary to consider in more detail and point-by-point those signs that show a noticeable effect on the error of the diagnosis. It is possible to weaken these signs in the model by setting the appropriate weights.

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Methodology for a Comprehensive Assessment of the Health Status of Premature Newborns with a Gestational Period of Fewer Than 30 Weeks

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Abstract The aim of the study is to develop, test, and refine a statistically reliable method for assessing the severity of the condition of premature newborns with a gestation period of fewer than 30 weeks at birth based on a multivariate statistical analysis of the data. The model of binary logistic regression was taken as a basis. Based on the available sample of precedents, a statistically reliable decision rule has been developed, on the basis of which a method for recognizing the severity of the condition of new patients can be developed. As an assessment of the severity of the newborn, the probability of its assignment to the corresponding group of patients was used. The results on the test sample of data showed high statistical reliability of the classification of patients. This allows us to use the proposed method to assess the health status of premature newborns and timely provide the necessary complex medical manipulations.

Keywords Preterm infants · Forecast · Model · Logistic regression · Discriminant analysis · Classification

1 Introduction

As a result of the introduction of modern technologies of intensive care and neonatal resuscitation, the number of surviving premature infants with a gestational age of fewer than 30 weeks is increasing annually. According to the International Classification of Diseases of the 10th revision (ICD-10) [1], prematurity is usually classified

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according to two criteria, taking into account both birth weight and gestational age. By bodyweight at birth, four degrees of prematurity are distinguished: Ist degree of prematurity with the body weight of 2500–2000 g., II degree with the body weight of 1999–1500 g., III degree of premature children born with a very low body weight of 1499–1000 g. and IV degree of prematurity, children born with extremely low body weight (ELBW) of 999–500 g. Taking into account the gestational age at birth, prematurity is divided as follows: Ist degree of prematurity 35–37 weeks of gestation, II degree of prematurity 32–34 weeks, III degree of prematurity 29–31 weeks, and IV degree of prematurity 22–28 weeks of gestation.

The use of artificial lung ventilation (ALV) is a widely used treatment for preterm infants with a gestational age of fewer than 30 weeks. Thus, 89% of newborns with EBMT require mechanical ventilation on the first day of life, and in 95% of surviving premature infants, respiratory support was used during inpatient treatment [2]. In addition, studies on the priority of invasive or non-invasive respiratory support revealed that non-invasive respiratory support for premature infants with EBMT at birth was used in 83% of cases, but these patients still needed mechanical ventilation during inpatient treatment [3]. Research by B.J. Stoll et al. showed that 74% of premature babies with a gestational age of fewer than 28 weeks. At birth, they required surfactant therapy during the period of inpatient treatment [4]. A study of newborns with a gestational age of 25–28 weeks at birth and a relatively stable respiratory activity at birth revealed that 46% of them subsequently needed to switch from non-invasive methods to intubation and mechanical ventilation [4].

In this regard, mechanical ventilation is currently actively used in premature infants with acute respiratory failure at birth, despite the fact that non-invasive methods have proven advantages over mechanical ventilation. Invasive ventilation can contribute to the occurrence of various complications, including increased risks of death, as well as the development in more distant periods of deviations in the neurological development of the child [2, 5].

Thus, the treatment of patients with EBMT at birth requires their extubation as early as possible in order to prevent the development of possible complications during mechanical ventilation. It was found that each additional week on mechanical ventilation is associated with an increase in the risk of subsequent neurological development delay in the child. In addition, the endotracheal tube, as a foreign body, can act as an entry gate for pathogens, increasing the risk of ventilator-associated pneumonia and sepsis [6].

According to some data, the success of the transition from invasive to non-invasive respiratory support ranges from 60–73% [7, 8] to 80–86% [9]. Neonates who have not been successfully extubated have a high risk of episodes of hypoxemia and hypercapnia, bradycardia, cerebrovascular accident, and atelectasis [10]. In this regard, the task of finding predictors of their effective and safe transition from mechanical ventilation to non-invasive respiratory support is very urgent and vital for this category of patients.

The morbidity structure of a patient with EBMT is characterized by a greater severity and combination of existing disorders due to morpho-functional immaturity, lack of intrauterine well-being of the fetus during pregnancy, and concomitant infectious pathology [11, 12]. One of the main tasks of the doctor of the intensive care unit is the timely recognition of the stage and depth of the pathogenetic process of the symptom complex of diseases in each specific case. The treatment tactics in such patients, based on medical experience and professional intuition, can be subject to a certain amount of error. Currently, technologies for modeling biological systems are being implemented in medicine. Such modeling is based on the use of digital technologies that allow doctors, regardless of the level of professional training and equipment of a medical institution, to choose personalized therapeutic tactics. An important condition for this is the simplicity and availability of mathematical models for institutions at all levels of medical care.

The aim of this work is to test and refine the previously developed statistically reliable method for assessing the severity of the condition of premature infants with a gestational age of fewer than 30 weeks at birth on the basis of multivariate statistical analysis of data on a larger sample of patients [13].

2 Research Objective

In the first stage, anamnestic data and the results of medical and diagnostic procedures were assessed in 62 premature infants who were in the department of anesthesiology and intensive care (with wards for newborns) of the State Institution “Republican Scientific and Practical Center “Mother and Child”, Minsk, Belarus.

20 signs were analyzed: anamnestic data, acid–base state of blood at birth, near-infrared spectroscopy (NIRS) for the first 24 h of a child’s life, respiratory support for a newborn, hemodynamic status, and hydro balance in the first 24 h of a child’s life. The analyzed signs are given in Table 1.

The examined patients required respiratory support. Examination time: for indicators X_1–X_6–in the delivery room, for indicators X_7–X_{20}–in the first 24 h of life. All premature infants were divided into two samples. The first sample consists of 32 newborns and is referred to as the training sample. It was used to investigate the fundamental possibility of a statistically significant classification of the state of newborns by severity. The second sample of 30 preterm infants is referred to as the test sample. According to it, the adequacy of the classification of the state of newborns proposed for the training sample is checked. And if the adequacy turns out to be satisfactory, then in the future, for the entire sample of 62 newborns, the condition is classified assessment and a methodology is developed for a comprehensive assessment of the health of premature newborns with a gestational age of fewer than 30 weeks.

Table 1 Anamnestic and laboratory data

Anamnesis	Sex: f–0, m–1	X_1
	Birth weight (g)	X_2
	Pregnancy: 0–singleton, 1–multiple	X_3
	Delivery method: 0–vaginal delivery, 1–elective caesarean section, 2–emergency caesarean section	X_4
Indicators of acid–base state	pH	X_5
Indicators of acid–base state	Lac	X_6
NIRS	crSO2 (average)	X_7
	ΔcrSO2 (max–min)	X_8
Pulse Oximetry	SpO2 MIN during mechanical ventilation	X_9
Clinical observation	Hemodynamic status	X_{10}
Acid–base state (arterial blood)	pH MIN	X_{11}
	pH MAX	X_{12}
	pCO2 MIN	X_{13}
	pCO2 MAX	X_{14}
	pO2 MIN	X_{15}
	pO2 MAX	X_{16}
	ctO2 MIN	X_{17}
	ctO2 MAX	X_{18}
	p50 MIN	X_{19}
	p50 MAX	X_{20}

3 Mathematical Models and Methods

For practical use, the method of assessing the health of premature newborns should, on the one hand, be simple and understandable for doctors. On the other hand, it should be based on a rigorous mathematical model that makes it easy to interpret the obtained results. Logistic regression responds to these conditions [14]. However, for its effective application, it is required to successfully select a set of diagnostic features that allow dividing the existing set of observations into clusters. In this case, despite the relative simplicity, classification methods based on logistic regression are more effective than more powerful recognition procedures.

Logistic regression proves to form a well-interpreted indicator of severity in the form of the probability of attributing a patient to a particular group of patients. For the two classes, it is as follows.

A training sample of feature values is given as $X_1, X_2, \ldots, X_m(\mathbf{x}_i, y_i)$, $i = 1, 2, \ldots, n$, where $\boldsymbol{x}_i = \begin{pmatrix} x_{i0} \\ x_{i1} \\ \cdots \\ x_{im} \end{pmatrix} = \begin{pmatrix} 1 \\ x_{i1} \\ \cdots \\ x_{im} \end{pmatrix}$—vector of values of the i-th object, $\boldsymbol{X} = \begin{pmatrix} 1 & x_{11} & \ldots & x_{1m} \\ 1 & x_{21} & \ldots & x_{2m} \\ \cdots & \cdots & \cdots & \cdots \\ 1 & x_{n1} & \ldots & x_{nm} \end{pmatrix}$; $X_j = \begin{pmatrix} x_{1j} \\ x_{2j} \\ \cdots \\ x_{nj} \end{pmatrix}$; $\boldsymbol{y} = \begin{pmatrix} y_1 \\ y_2 \\ \cdots \\ y_n \end{pmatrix}$, $y_i \in \{0;\ 1\}$—binary variable indicating affiliation of the i-th object to the corresponding class, for example, to the first class at $y_i = 0$ and to the second–at $y_i = 1$; m is the number of features for each object; n is the number of observations. The classification is performed using the logistic function [14]

$$h(\boldsymbol{x}) = \frac{1}{1 + \exp\{-\boldsymbol{b}^T \boldsymbol{x}\}}, \tag{1}$$

taking values in the interval (0; 1). The threshold is $h(\boldsymbol{x}) = 0,5$. Vector $\boldsymbol{b} = (b_0\ b_1\ \ldots\ b_m)^T$ in (1) defines a separating linear boundary described by the hyperplane equation $\Pi:\ \ \boldsymbol{b}^T \boldsymbol{x} = 0$.

Let us introduce the function $W(\boldsymbol{x}) = \boldsymbol{b}^T \boldsymbol{x}$. Let us define the region D1 of possible values of x for the first class as $D_1 = \{\boldsymbol{x} : W(\boldsymbol{x}) < 0\}$, and for the second class as $D_2 = \{\boldsymbol{x} : W(\boldsymbol{x}) > 0\}$. Тогда $\forall \boldsymbol{x} \in D_1$ $h(\boldsymbol{x}) < 0,5$ и $\forall \boldsymbol{x} \in D_2$ $h(\boldsymbol{x}) > 0,5$. If x belongs to the hyperplane $\prod$, then $h(\boldsymbol{x}) = 0,5$. Those. for an arbitrary observation of x*, the probability of its assignment to the first class is equals $P(\boldsymbol{x}^* \in D_1) = 1 - h(\boldsymbol{x}^*)$, and to the second class $P(\boldsymbol{x}^* \in D_2) = h(\boldsymbol{x}^*)$.

In [14], a method was proposed for calculating the coefficients of the vector b by solving the problem $Q(\boldsymbol{b}) = \sum_{i=1}^{n} \ln\left(1 + e^{-y_i \boldsymbol{b}^T \boldsymbol{x}_i}\right) \to \min\limits_{\boldsymbol{b} \in \boldsymbol{R}^m}$.

The vector of coefficients b is estimated by different algorithms, for example, the Newton–Raphson algorithm is used [15, 16]. However, with the correct classification of all observations, the objective function $Q(\mathbf{b})$ has a zero lower bound at infinity and therefore problem (4) will not have an exact solution. An increase in the components of vector b causes an unlimited increase in some values $-y_i \boldsymbol{b}^T \boldsymbol{x}_i$. As a result, computational errors grow, leading to memory overflow and stopping the algorithm [16].

The program [17] was used to estimate the vector of coefficients b. It implements a zero-order algorithm that uses a random search with a fixed length of the vector b, described in [18], at each iteration. This eliminates the uncontrolled growth of computational errors [19] and ensures the stability of the algorithm.

4 Results and Discussion

Cluster analysis revealed the presence of two groups of premature children according to the severity of their health conditions, which were defined as "severe" (D_1) and "very severe" (D_2) [20, 21].

Thus, taking into account the conclusions of the cluster analysis, based on the results of a complete medical examination, a training sample was formed: 21 patients were assigned to group D_1, and 11 patients to group D_2. The solution to the classification problem is to try to distinguish between the groups of patients D_1 and D_2 and, if successful, to construct a decision rule for classification. To do this, it was necessary to solve the problem of multidimensional classification (recognition) of two groups (clusters) in terms of anamnestic data and the results of medical and diagnostic procedures X_1–X_{20}. The essence of the solution consists in finding such a set of indicators from the initial set that would allow (if it is possible in principle) to statistically reliably recognize the differences in these groups. This task was solved in two stages. First, using discriminant analysis, a system of informative features was formed, and then, using logistic regression, a decisive classification rule was built.

Using discriminant analysis [22, 23] in the Statistica package, a discriminant function was constructed with a minimum p-level that was less than 0.0001. The following qualitative and quantitative indicators were informative ones: X_3, X_4, X_6, X_8, X_9, X_{10}, X_{14}, X_{16}, X_{17}, X_{18}. Recognition of two groups (D_1) and (D_2) was statistically reliable since all the indicators have high statistical reliability (over 98%). This means that the formed system of indicators sufficiently distinguishes between "severe" and "very severe". All patients from the training sample were correctly classified.

Then, based on statistically significant features obtained using discriminant analysis, the decision rule of classification was constructed in the form of binary logistic regression. To ensure the computational stability of the algorithm for constructing the logistic regression, a data standardization procedure was performed (bringing the indicators to zero mean and unit variances). The integrative predictive index has the following form:

$$\begin{aligned} Z = b_0 + b_3X_3 + b_4X_4 + b_6X_6 + b_8X_8 + b_9X_9 \\ + b_{10}X_{10} + b_{14}X_{14} + b_{16}X_{16} + b_{17}X_{17} + b_{18}X_{18}, \end{aligned} \tag{2}$$

where $b_0 = 7.268$, $b_3 = -10.171$, $b_4 = 7.229$, $b_6 = -20.056$, $b_8 = 2.388$, $b_9 = 18.367$, $b_{10} = -8.374$, $b_{14} = -9.813$, $b_{16} = -3.721$, $b_{17} = 16.845$, $b_{18} = -16.898$.

If the result calculated according to the predictive rule (2) is less than zero, then the child is predicted to have a "very severe" condition with probability $P_0 = e^{-Z} / 1 + e^{-Z}$. If the result Z is greater than zero, then the child is predicted to have a "severe condition" with probability $1-P_0 = 1 / 1 + e^{-Z}$. Group D_1 included 21 patients, group D_2–11 patients. All patients were correctly classified.

In the second stage, we will check the quality of recognition according to the predictive rule (2) using a test sample of another 30 premature infants with an established severity of health. Here, as before, the data standardization procedure was carried out.

Table 2 shows the results of recognizing the state of health of patients. Shown here are: №№—observation number (serial number of the patient in the total sample; IND—belonging of observations to one of the groups (IND = 0—group "severe",

Table 2 Results for the test group of patients

№№	*Z*	P_0	$1 - P_0$	*IND*	*W*
33	23.10	1.00000	0.00000	0	0
34	18.58	1.00000	0.00000	1	0
35	19.90	1.00000	0.00000	0	0
36	−27.15	0.00000	1.00000	1	1
37	−21.62	0.00000	1.00000	0	1
38	12.59	1.00000	0.00000	0	0
39	−20.43	0.00000	1.00000	1	1
40	12.54	1.00000	0.00000	1	0
41	45.24	1.00000	0.00000	0	0
42	51.95	1.00000	0.00000	0	0
43	30.75	1.00000	0.00000	0	0
44	−1.13	0.24402	0.75598	1	1
45	39.53	1.00000	0.00000	1	0
46	−26.74	0.00000	1.00000	1	1
47	−17.34	0.00000	1.00000	1	1
48	26.42	1.00000	0.00000	1	0
49	35.11	1.00000	0.00000	0	0
50	−10.55	0.00003	0.99997	1	1
51	−33.56	0.00000	1.00000	1	1
52	−54.39	0.00000	1.00000	1	1
53	11.27	0.99999	0.00001	0	0
54	−153.40	0.00000	1.00000	1	1
55	47.60	1.00000	0.00000	0	0
56	43.19	1.00000	0.00000	0	0
57	−14.01	0.00000	1,00,000	1	1
58	32.31	1.00000	0.00000	0	0
59	17.55	1.00000	0.00000	0	0
60	−67.33	0.00000	1.00000	1	1
61	–109.48	0.00000	1.00000	1	1
62	−110.01	0.00000	1.00000	1	1

IND = 1—group “very severe”); P_0—probability of attribution of the patient group “very severe” (IND = 1); 1–P_0—the probability of referring the observation (child) to the group “severe” (IND = 0); W—group calculated for patients according to the prognostic rule (2) ($W = 0$—group “severe”, $W = 1$—group “very severe”).

According to Table 2, five out of thirty patients were misclassified (№№ 34, 37, 40, 45, 48), which is 16.7%. This discrepancy is explained by a sufficiently small training sample for constructing a predictive rule (1). It should be noted that for the used training sample of 32 observations, this is an acceptable result, which gives grounds to speak of a successful choice of the feature space.

Now we consider all 62 observations as a training sample (32 patients from the training sample plus 30 new patients from the test sample). Boys were 31/50.00%, girls 31/50.00%. 44 newborns were from singleton pregnancies (70.97%), 18—from multiple pregnancies (29.03%). The mean gestational age of the infants was 28.095 ± 0.947 weeks. At the same time, 24 newborns had III degree of prematurity and 38 infants had IV degree of prematurity by gestational age.

The body weight at birth was 1061.774 ± 222.501 g, the III and IV degrees of prematurity by body weight were 31 babies in each group. The indicated clinical data of patients indicate that the studied sample was formed from an extremely severe group of resuscitation pediatric patients.

Three children were born through the vaginal birth canal (3/4.84%), with abdominal delivery—59/95.16% of infants (38/64.41%—with emergency and 21/35.59%—with planned delivery).

All the children (62/100.00%) in the delivery room received surfactant replacement therapy at a dose of 248.639 ± 88.903 mg/kg.

The discriminant analysis showed that in this case the indicators $X_2, X_3, X_4, X_5, X_8, X_9, X_{10}, X_{14}, X_{16}$, will be statistically significant (p-level less than 0.05), i.e. only three features have been updated here.

Table 3 shows the results of discriminant data analysis. The discriminant function was constructed with the minimum p-level, which was less than 0.0001. The resulting

Table 3 Results of checking the statistical significance of signs for the test group of patients. Checking for signs

$N = 62$	Wilks' Lambda	Partial Lambda	F-remove (1,52)	p-level	Toler	1-Toler. (R-Sqr.)
X_2	0.412069	0.772869	15.28175	0.000269	0.899895	0.100105
X_3	0.352599	0.903224	5.57155	0.022040	0.623400	0.376600
X_4	0.378558	0.841285	9.81020	0.002848	0.702582	0.297418
X_5	0.361625	0.880678	7.04540	0.010520	0.806026	0.193974
X_8	0.343239	0.927854	4.04332	0.049545	0.828758	0.171242
X_9	0.378875	0.840583	9.86185	0.002782	0.845847	0.154153
X_{10}	0.420119	0.758061	16.59610	0.000158	0.816686	0.183314
X_{14}	0.362440	0.878699	7.17838	0.009857	0.682157	0.317843
X_{16}	0.347697	0.915957	4.77121	0.033472	0.888109	0.111891

model includes features whose p-level turned out to be less than 0.05, i.e. all indicators turned out to be statistically significant with reliability higher than 0.95.

Based on the formed diagnostic features, an integrative prognostic index was built as follows.

$$Z = b_0 + b_2X_2 + b_3X_3 + b_4X_4 + b_5X_5 + b_8X_8 + b_9X_9 + b_{10}X_{10} + b_{14}X_{14} + b_{16}X_{16}, \quad (3)$$

where $b_0 = 2.312$, $b_2 = 7.488$, $b_3 = –6.937$, $b_4 = 3.601$, $b_5 = 7.039$, $b_8 = 2.436$, $b_9 = 11.227$, $b_{10} = –6.559$, $b_{14} = –6.050$, $b_{16} = –8.604$.

Rule (3) made it possible to correctly classify all 62 patients. The classification results are shown in Tables 4 and 5.

Analysis of Tables 4 and 5 shows that all patients were recognized, there is not a single case when the probability P_0 would be close to the borderline situation of 0.5. Thus, based on a sample of 62 observations, we obtained a variety of diagnostic indicators for recognizing the health status of premature newborns.

Let us compare the considered groups of premature newborns using entropy analysis [24, 25]. Here, as before, the data standardization procedure was carried out.

The results of vector entropy analysis for statistically significant indicators are shown in Table 6.

We can see that in the "very severe" group, compared with the "severe" group, the entropies of chaos and self-organization are much higher (the entropy of chaos is 2.87 or 27.4% higher, and the entropy of self-organization is greater by 0.42 or 38.4%). This means that in "very severe" newborns, in general, the variation in indicators, their variability is higher, and the tightness of the relationship between indicators is lower. Accordingly, the total entropy of "very severe" is 3.29 or 35.4% higher than that of "severe" ones. Thus, from the point of view of considering the organism as a complex system, the elements (informative diagnostic indicators) in the group (in the system) "very severe" behave more chaotically and interact much less in comparison with the elements of the group (of the system) "severe".

5 Conclusion

The combination of a set of signs of anamnestic data, signs of acid–base state at birth, signs of respiratory support of the newborn, hemodynamic status, and NIRS allows us to reliably judge the severity of the condition of premature infants with a gestational age of fewer than 30 weeks.

The use of the calculated decisive rule when working with premature newborns is an affordable technique that can help doctors diagnose in advance the severity of the pathological process occurring in the child's body and provide the necessary

Table 4 Classification results for the training sample of patients

№№	Z	P_0	$1 - P_0$	IND	W
1	−18.51	0.00000	1.00000	1	1
2	−8.03	0.00033	0.99967	1	1
3	5.11	0.99399	0.00601	0	0
4	13.54	1.00000	0.00000	0	0
5	−18.53	0.00000	1.00000	1	1
6	−14.53	0.00000	1.00000	1	1
7	10.47	0.99997	0.00003	0	0
8	12.44	1.00000	0.00000	0	0
9	4.81	0.99191	0.00809	0	0
10	18.06	1.00000	0.00000	0	0
11	−13.43	0.00000	1.00000	1	1
12	6.65	0.99871	0.00129	0	0
13	3.13	0.95808	0.04192	0	0
14	−6.34	0.00176	0.99824	1	1
15	12.09	0.99999	0.00001	0	0
16	−5.18	0.00559	0.99441	1	1
17	−23.23	0.00000	1.00000	1	1
18	12.20	0.99999	0.00001	0	0
19	22,82	1.00000	0.00000	0	0
20	4.63	0.99034	0.00966	0	0
21	12.15	0.99999	0.00001	0	0
22	3.44	0.96881	0.03119	0	0
23	14.28	1.00000	0.00000	0	0
24	18.51	1.00000	0.00000	0	0
25	27.44	1.00000	0.00000	0	0
26	−23.91	0.00000	1.00000	1	1
27	29.34	1.00000	0.00000	0	0
28	27.17	1.00000	0.00000	0	0
29	−61.59	0.00000	1.00000	1	1
30	16.19	1.00000	0.00000	0	0
31	37.22	1.00000	0.00000	0	0
32	−44.44	0.00000	1.00000	1	1

Table 5 Results of classification for the test sample of patients

№№	Z	P_0	$1 - P_0$	IND	W
33	31.98	1.00000	0.00000	0	0
34	−2.42	0.08198	0.91802	1	1
35	34.84	1.00000	0.00000	0	0
36	−3.11	0.04284	0.95716	1	1
37	16.57	1.00000	0.00000	0	0
38	13.72	1.00000	0.00000	0	0
39	−11.64	0.00001	0.99999	1	1
40	−6.69	0.00124	0.99876	1	1
41	13.41	1.00000	0.00000	0	0
42	32.14	1.00000	0.00000	0	0
43	34.41	1.00000	0.00000	0	0
44	−10.10	0.00004	0.99996	1	1
45	−13.28	0.00000	1.00000	1	1
46	−14.64	0.00000	1.00000	1	1
47	−9.54	0.00007	0.99993	1	1
48	−12.56	0.00000	1.00000	1	1
49	22.31	1.00000	0.00000	0	0
50	−17.45	0.00000	1.00000	1	1
51	−30.23	0.00000	1.00000	1	1
52	−6.70	0.00123	0.99877	1	1
53	11.94	0.99999	0.00001	0	0
54	−39.19	0.00000	1.00000	1	1
55	27.01	1.00000	0.00000	0	0
56	34.29	1.00000	0.00000	0	0
57	−9.94	0.00005	0.99995	1	1
58	24.80	1.00000	0.00000	0	0
59	3.09	0.95646	0.04354	0	0
60	−5.65	0.00350	0.99650	1	1
61	−74.17	0.00000	1.00000	1	1
62	−48.63	0.00000	1.00000	1	1

Table 6 Results of vector entropy analysis of groups “severe” (IND = 0) and “very severe” (IND = 1)

IND	Entropy of chaos H_V	Entropy of self-organization H_R	Total entropy H
0	10.47	−1.11	9.37
1	13.34	−0.68	12.66

complex of therapeutic manipulations in a timely manner to stabilize the condition of patients in intensive care units for newborns.

Vector-entropy analysis showed a significant difference in the behavior of groups of premature newborns "severe" and "very severe" as complex multi-dimensional systems. Informative diagnostic indicators in the "very severe" group behave more chaotically and interact much less in comparison with the elements of the "severe" group.

The obtained results can be introduced into the practice of children's intensive care units at various levels of perinatal care for newborn children.

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Application of Biosignals in the End-to-End Encryption Protocol for Telemedicine Systems

T. I. Buldakova and D. A. Krivosheeva

Abstract The problem of data protection in telemedicine systems is investigated. As an example of such systems, a telemedicine system for remote monitoring of a person's state is considered. The features of the remote monitoring system, an integral part of which is a mobile measuring complex for receiving, recording, and processing human biosignals, are noted. The solutions developed during the monitoring process are based on the received data and the results of their analysis. Therefore, it is necessary to ensure the protection of the transmitted data in remote monitoring systems of the human state. The relevance of research in the field of information security of telemedicine systems is noted and the task of ensuring the integrity, availability, and confidentiality of data is set. To protect personal data, it is proposed to use end-to-end encryption, for which it is necessary to choose a method for distributing cryptographic keys. It is shown that the appropriate processing of the recorded biosignals allows us to obtain the necessary information for constructing keys. The processing is based on the reconstruction of a mathematical model that generates time series that are diagnostically equivalent to the original biosignals. The examples and results of such processing are given.

Keywords Protection of Information · Telemedicine · Biosignals · Reconstruction of System Model

1 Introduction

The modernization of the healthcare system is accompanied by the active introduction of information and communication technologies that ensure the formation of channels of sustainable communication between specialists of different medical and preventive institutions, remote access to medical information systems (MIS), and facilitate and speed up the registration of patients for appointments with doctors [1–4]. An example of the development of virtual healthcare infrastructure is telemedicine systems, which

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remotely provide patients with highly qualified assistance from doctors of leading medical centers [5–7].

In such telemedicine systems for remote monitoring of human health, cloud computing technologies are increasingly used, when a system of wearable sensors is installed on the patient, which registers physiological information (mainly biosignals) and transmits it wirelessly to the server. Medical personnel can view the collected information in real-time in the medical information system containing the biosignal database and assess the current functional state of the patient.

When creating telemedicine systems, an important task is to ensure information security [8, 9]. Such systems process not only personal data, but also demographic, financial, and medical information. Therefore, it is necessary to ensure the security of the personal data processed by the system and the information that constitutes a medical secret.

This issue is particularly acute in remote monitoring of the human state. The lack of real security capabilities can not only lead to data privacy violations but also potentially allow hackers to harm the patient by altering real physiological data, leading to incorrect diagnosis and treatment. Taking into account the international requirements of the *Health Insurance Portability and Accountability Act* (HI-PAA), the protection of personal medical data is absolutely necessary (http://www.hhs.gov/ocr/hipaa/). Thus, the task of improving information protection methods in systems for remote monitoring of a person's state is very urgent.

2 Features of the Telemedicine System for Remote Monitoring of a Person's State

Currently, telemedicine systems for monitoring the human state are becoming more widespread. First of all, they are used for monitoring the state of elderly people, patients with chronic diseases, and in the process of rehabilitation, as well as for assessing the state of operators of cyber-physical systems [10–13].

The modern telemedicine complex is created on the basis of a powerful computer, which is easily interfaced with a variety of medical equipment, means of short- and long-range wireless communication, video conferencing, and IP broadcasting. An important area of development of remote monitoring of the patient's state is the integration of various biosignal sensors into clothing, various accessories, and mobile phones [14, 15].

Sensors that allow registering human biosignals (electrical activity and heart contractions, pulse signal, electrical activity of the brain, external respiration function, etc.), act as sources of primary information. Therefore, a mobile measuring system is an integral part of the telemedicine system for remote monitoring of the person's state. It performs the recording, registration, and primary processing of biosignals.

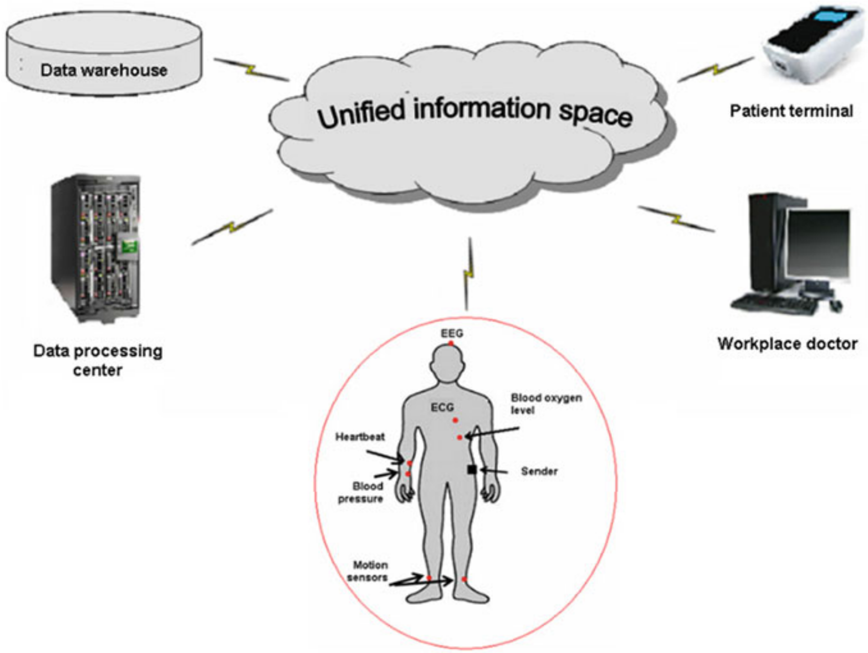

Fig. 1 Organization of remote monitoring of a person's state

The inclusion of such a mobile measuring system in a single information space provides continuous monitoring of a person's state regardless of his location (Fig. 1).

Sensors can send data to the cloud directly or via intermediate base stations. Service personnel and the user can view the collected medical information directly from the cloud using a smartphone or via the Internet in real-time and make decisions in accordance with the current functional state of the person.

However, given the possible access to information (including unauthorized access) of various specialists, methods and technologies are required to protect the personal data of patients.

3 End-to-End Encryption for Sensitive Data Transfers

The created threat model and its analysis showed that there is a problem of ensuring the information security of patient data [16]. At the same time, it is crucial to protect personal medical information when it is transmitted via a communication channel from sensors to a cloud-based medical database.

Unlike traditional systems for monitoring the state of a person, where the server can be reliably protected from external threats, in the technology of "cloud" computing the server is virtual and, in essence, is a rented computing resource accessible via the Internet. The information vulnerability of such a server is much higher.

The modern approach to securing the transmitted data is End-to-End Encryption (E2EE)—a method of data transfer when only users involved in communication have access to messages.

End-to-end encryption is designed to prevent data from being read or secretly altered by other than the true sender and receiver. Messages are encrypted by the sender, the recipients receive the encrypted data and decrypt it themselves. The third-party has no means of decrypting them. End-to-end encryption prevents attackers from gaining access to the keys needed to decrypt messages.

The E2E protocol works by setting and then distributing cryptographic keys between the sensors and the cloud, which ensures data secrecy and integrity. The main difficulty lies in the possibility of confidential distribution (delivery) of keys to users of the system. In this regard, to protect the transmitted personal information, it is necessary to choose a method for distributing cryptographic keys between the sensor and the cloud to ensure the encryption and integrity of the data.

Let's consider possible approaches to the implementation of the protocol for telemedicine systems.

Traditionally, asymmetric cryptosystems are used to ensure the security of health systems, when two different keys are used: one for encoding, the other for decoding messages (Fig. 2). This is sufficiently reliable to ensure the confidentiality and integrity of the transmitted data [17, 18]. However, for the regular exchange of data in real-time (which is typical for remote patient monitoring systems), this approach is time-consuming and resource-intensive due to the large length of the keys.

The use of paired keys (ie, symmetric cryptosystem) significantly reduces these costs, but there is another drawback—the impossibility of authorization confirmation since the key is known to each party (Fig. 3).

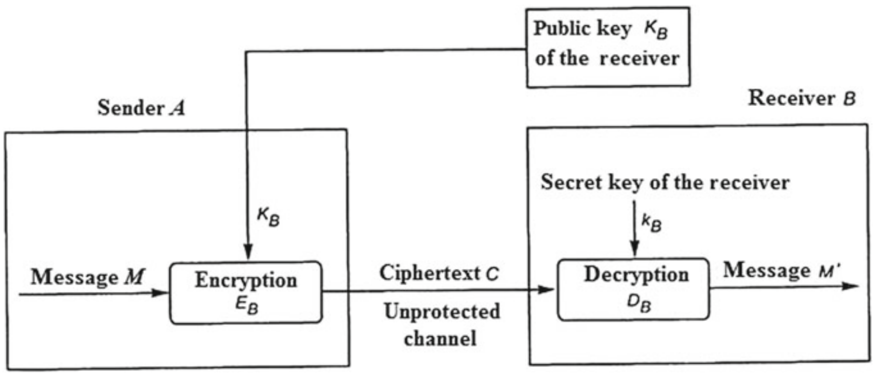

Fig. 2 Data transmission using an asymmetric cryptosystem

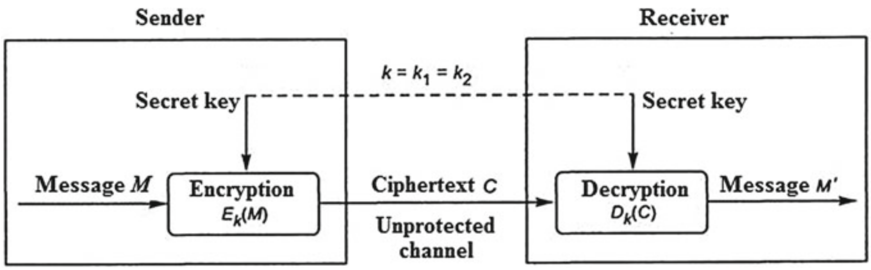

Fig. 3 Data transmission using a symmetric cryptosystem

Thus, to implement end-to-end encryption in telemedicine systems, it is necessary to solve the problem of the covert distribution of cryptographic keys between the participants of the process.

4 Using Biosignals to Hide Information

Currently, there are works that suggest overcoming this difficulty and improving the reliability of symmetric cryptographic keys by using biosignals recorded by sensors. Biosignals reflect the physiological characteristics of the patient and can therefore be used to hide information [19–22]. For example, in [23], some morphological features of biosignals, which are unique to humans and which change little over time, are identified (Fig. 4).

In addition, physiological signals can be artificially generated using a generator model, provided that this model is adequately constructed on the basis of information about the human state [24]. The marked properties of the biosignals make it possible to use them to create keys. The necessary information (morphological features of a particular person's biosignals) is extracted at the first signal registration.

The use of biosignals for end-to-end encryption of data transmitted from the sensor to the object is implemented in the protocol PEES (Physiology-based End-to-End Security). Note that the PEES network protocol using patient biosignals does not require a priori key distribution. To create a secure E2E communication, it is enough to simply install the sensors on a person during the first visit to a medical specialist. In the cloud, inside the storage, the diagnostic equivalent of biosignals is stored in the form of time series created using a model generator, which must be tuned according to the patient's physiological data (Fig. 5).

To implement this approach, it is necessary to choose a method for constructing a model for generating artificial physiological signals. Let's consider two biosignals—ECG and PPG.

In [23], an artificial ECG generator is described by the expression

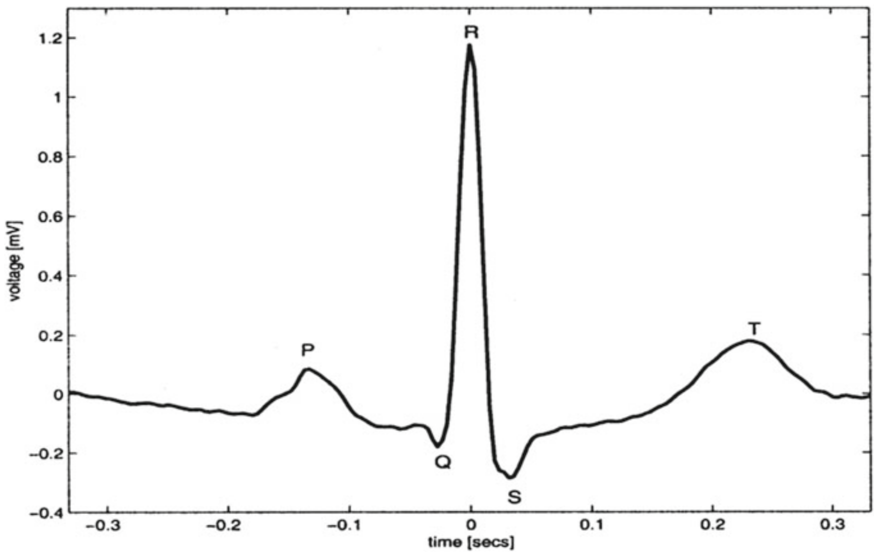

Fig. 4 Morphological *PQRST* parameters of the ECG signal of a healthy person

$$\frac{dECG(t)}{dt} = -\sum_{i \in P,Q,R,S,T} a_i (2\pi hr_{mean} t - \theta_i) e^{\left(\frac{-(2\pi hr_{mean} t - \theta_i)^2}{2b_i^2}\right)},$$

where hr_{mean}—average heart rate of a person. Time-varying parameters include heart rate mean, heart rate standard deviation, and *LF*/*HF* ratio.

To determine morphological parameters, each type of P, Q, R, S, and T waves on the ECG is represented by a Gaussian curve. Each curve has three parameters, and therefore there are 15 morphological parameters (aP, aQ, aR, aS, aT, bP, bQ, bR, bS, bT, θP, θQ, θR, θS, θT).

The photoplethysmogram curve (PPG) is obtained as a result of solving differential equations based on a simple model of the human vascular system—the Windkessel model [25]. PPG is divided into two parts—systole and diastole. Diastole is modeled using the equation:

$$PPG_{dias}(t) = a_1 + a_2 e^{(-a_3 t)} + \frac{1}{a_4 + e^{(-a_5 t - a_6)}} \cdot \cos(a_7 t + a_8). \quad (1)$$

For systole, the analytical expression for the waveform is:

$$PPG_{sys}(t) = \frac{1}{a_9 + e^{(-a_{10} t - a_{11})}}. \quad (2)$$

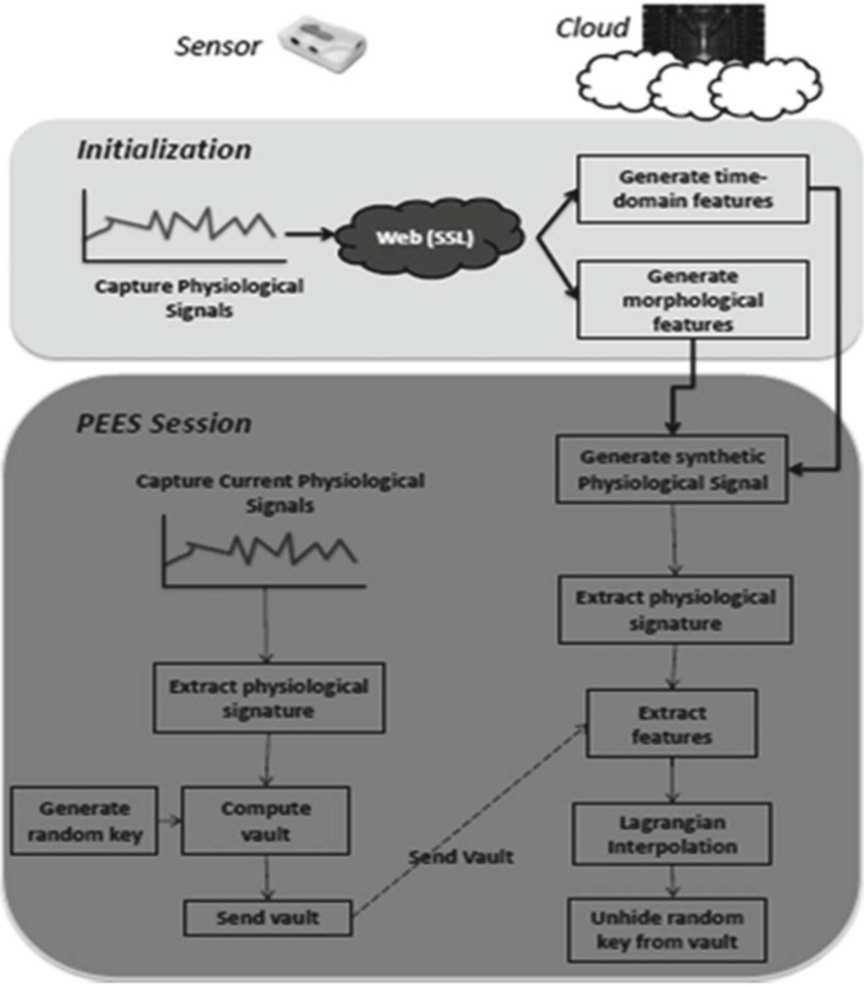

Fig. 5 Provision of information security using the *PEES* protocol [23]

The morphological parameters are the coefficients [a1, a2, …, a11] in Eqs. (1) and (2). Timing parameters include heart rate, heart rate standard deviation, and LF/HF ratio.

In essence, the work [23] used the reconstruction of functional dependencies using time series (biosignal records), where the selection of functional dependencies was carried out based on the shape of the recorded ECG and FPG biosignals. A result is a large number of morphological parameters, which should be considered as a multidimensional characteristic vector (morphological vector). If we take into account that the calculation of these morphological parameters using the least-squares method is a poorly conditioned task, we come to the conclusion that in practice such a morphological vector does not have the necessary stability.

5 Proposed Solution

To eliminate the indicated drawback of the PEES protocol, it is proposed to use not separate parameters of the time curve, but a mathematical model of a biosignal generator in the form of a system of differential equations, as morphological signs. In this case, the structure of the model and its parameters become morphological features, and the task of determining morphological features is reduced to the task of reconstructing the model of the system. The key generation process is performed in accordance with the PEES protocol and is studied in detail in [23].

The model approach to the analysis of systems using reconstruction has proven itself well in the processing of human biosignals [20]. Let us consider the application of this approach when using a sphygmogram that registers fluctuations in the arterial wall caused by the release of the shock volume of blood into the arterial bed.

In [7, 16], the dynamic properties of the vascular wall are described by the autonomous Van der Pol-Rayleigh equation:

$$\ddot{x} + \left[\varepsilon_1\left(x^2 - r^2\right) + \varepsilon_2\left(\dot{x}^2 - \omega_0^2 \cdot r^2\right)\right] \cdot \dot{x} + ax = P(\omega_0 t), \tag{3}$$

where x—the movement of the artery wall detected by the sensor; $P(\omega_0 t)$—the effect of cardiac activity on the dynamics of the vessel wall; ε_1, ε_2, a, ω_0 and r—model parameters that determine the fluctuations of the blood vessel wall (frequency, amplitude, etc.). In this case, the ECG signal is the input of the model system, and the sphygmogram is the output.

Since the “heart-vessels” system operates in the limit cycle mode, the unknown parameters ω_0 and r of the model (3) can be determined from experimental data, after which the values p_i, a, ε_1 and ε_2 are found using the measured values $x(t)$ and the calculated values $\dot{x}(t)$ and $\ddot{x}(t)$. Here p_i is the coefficients of the expansion of the function P into the Fourier series, where i = 1, …, N.

The simulation results are shown in Fig. 6, where the output (pulse) signals of a person and the model system are shown.

The presented results, which demonstrate the similarity of the dynamic behavior of a real object and its model, confirm the good adequacy of the model with respect to the main dynamic properties. In addition, the advantage of the presented model is that the parameter a has a physical meaning: it allows you to evaluate the "stiffness" of the vessels due to the work of the smooth muscles that envelop them.

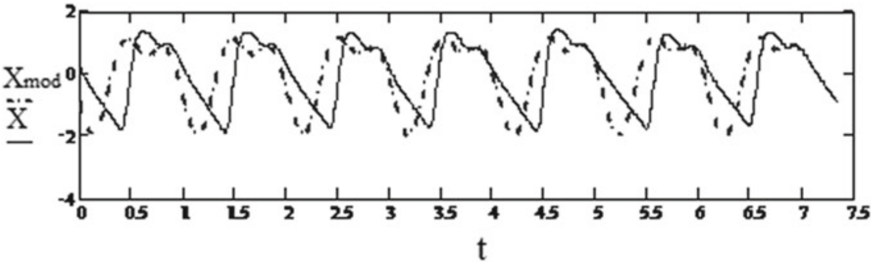

Fig. 6 Simulation results

6 Results

The proposed model (3) makes it possible to take into account various states of a person (Fig. 7) since they correspond to different values of the model parameters a, ε_1, and ε_2. The figure shows that in addition to increasing the frequency, the shape of the biosignals also changes. For example, for a healthy person at rest, the following values are obtained: $\varepsilon_1 = -0{,}3$; $\varepsilon_2 = -3{,}37$; $a = 36{,}15$. In a stressful state with an intense load for the same person, the parameters received the following values: $\varepsilon_1 = -1{,}07$; $\varepsilon_2 = -8{,}31$; $a = 95{,}5$.

The parameters of Eq. (3), reflecting such properties of the vessel as compliance and dissipation, are inherent in any vessel and, at the same time, are unique for an individual person.

Thus, it is necessary to embed into the PEES protocol not a large number of morphological features, as was done in [23], but information about the structure of the model equation (for example, Van der Pol-Rayleigh or Van der Pol-Duffing) and also the values of its parameters [16].

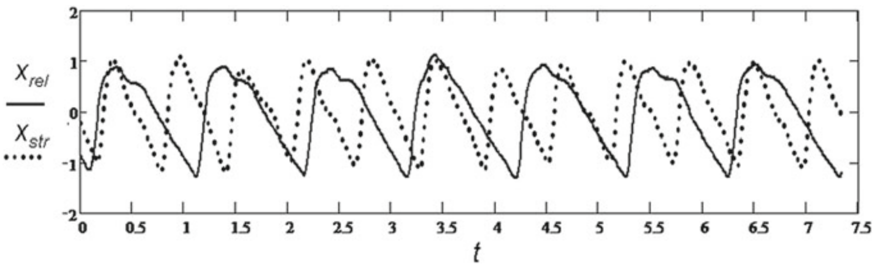

Fig. 7 Pulse signals at rest and under stress load

7 Conclusion

Studies have shown that as a result of the use of biosignals, the efficiency of end-to-end encryption increases and it becomes possible to prove authorship in a symmetric cryptosystem.

An approach is proposed in which a reconstructed mathematical model of a biosignal generator is used to construct cryptographic keys. The data protection method based on this approach is demonstrated by the example of the "heart-vessels" biosystem. It is shown that the model of the pulse mechanism in the form of a reconstructed mathematical model of a biosignal generator can be used in a security system to verify the authenticity of a message by comparing the features of the original and reconstructed signals.

Implementation of this method in monitoring systems will allow not only to improve the adequacy of the patient's state assessment based on multiple non-invasive measurements but also to form morphological signs for the formation of a "physiological" signature of a person. These characteristics include the structure of the model used to assess the human state and its physiologically significant parameters.

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The Stochastic Properties and Singular Analysis of Hankel Trajectory Matrices for Random Time Series in Biomedicine

Vladimir Kulikov, Alexander Kulikov, Valery Khranilov, and Alexander Ignatyev

Abstract The chapter presents the results of the study of stochastic properties of Hankel matrices for time series in current problems of medicine and natural science: fractal EGEG signal in gastroenterology, time series of Wolf numbers for biomedical purposes; chaotic processes–solutions of a system of nonlinear differential Chua equations as a potential model of some chaotic processes in biomedicine (electroencephalography). The possibilities of the developed methods are shown for identifying various probabilistic processes, which enable to reveal and restore with high resolution the laws of distribution with polymodal specificity. For illustration, the identification of the bimodal distribution of one of the components in the chaotic solution for Chua's strange attractor is noted. The conducted studies are relevant for the creation of mathematical models of human body structures, organs, and systems displaying their stochastic and chaotic properties under extreme conditions, including during long-term space expeditions. The distribution densities for singular values of the SVD-decomposition of Hankel trajectory matrices are identified in the perturbation method. The SSA method is used to decompose time series into interpreted additive constituents: regular components and noise with different distribution densities. The instability of chaotic Chua oscillations to disturbance with normal distribution is shown.

Keywords Cyber-physical system (CPS) · Biomedicine · EGEG-signal · Wolf-numbers · Chua equations · Polymodal densities · SSA-method · Diagnostics

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1 Introduction

This chapter covers the study of stochastic properties of distribution densities for singular values in the SVD decomposition of Hankel trajectory matrices using the SSA method. The stochastic properties of Hankel matrices have been investigated for the following three heterogeneous random processes: (a) a fractal EGEG signal in gastroenterology; (b) a random time series of Wolf numbers for biomedical purposes (heliobiology); (c) chaotic processes–solutions of the Chua's system of differential equations (SDE) as a potential model of some chaotic processes in biomedicine (electroencephalography). The identification was as before performed by the approximate solution of the first kind Fredholm equation in limited sampling [1].

The selection of cyber-physical biomedicine as an applied line of research has not been made at random. The current mathematical methods for analyzing experimental data in cyber-physical systems of medical monitoring are successfully used to diagnose and control treatment processes [2–4]. It is obvious that physiological processes in health and disease shall be studied in terms of random processes and variables which display themselves as complex polymodal distributions of biosignal parameters and have either fractal or chaotic nature.

It should be noted that electrogastroenterography is currently fast-developing as an alternative to probe diagnostic methods [5–8]. The referred papers are mainly limited to using algorithms of the wavelet analysis. In this regard, the work of Dr. Matsuura Y. and his colleagues is good development of the conventional trend [9].

The study of stochastic and singular features of the EGEG fractal signal in gastroenterology is described in the present authors' paper published by Springer early in 2021 [10]. Bioelectric signals of this kind are rightfully classified as quasi-fractal random processes. In other terms, this is a stochastic model of the fractional Brownian motion.

We have shown that methods for identifying distributions of local realizations or a signal as a whole can be promising techniques to analyze probabilistic and persistent properties of fractal signals. The statement that fractal processes and fluctuations shall be in general characterized by polymodal distributions has been proved by experimental data and mathematical models.

A similar approach is suggested for testing to create mathematical models for human body structures, organs, and systems displaying chaotic properties, including in terms of nonlinear dynamic systems. Relevant information on classical chaotic oscillators (of Lorentz, Chua), including the identification of latent oscillations and attractors in engineering systems, is contained in [11–17].

This chapter makes some initial steps in the study of chaotic processes and is aimed at biomedicine.

The second aspect of the study is associated with the elaboration of algorithms for compiling trajectory matrices of the EGEG signal, a time series of Wolf numbers, and chaotic Chua oscillations for the further stochastic and singular analysis of these matrix operators.

Information on the singular spectral analysis (SSA-method) is provided in [18–20]. This method is based on the singular value decomposition of trajectory matrices and the columns thereof are sliding segments of a series with length L, where L is an integral number–the "window length". It is also therein shown that the time series (random process) is surely displayed into the trajectory matrix (Hankel matrix).

Nevertheless, the method has some problems lacking a regular solution, namely: the identification of noise levels comparable to amplitudes of useful components, the discrimination of different noises, etc. A comprehensive approach suggested by the authors enables to conduct of a correct and prompt comparative analysis of EGEG or any other biosignals for patients in normal and different pathological states.

The relevance for the creation of such monitoring expert systems is currently noted in space medicine, particularly, in the Splanch experiment held by the RF State Scientific Center–the IBMP RAS using Gastroscan GEM or Splanchograph for studying structural and functional states of the digestive system in space flight (zero-gravity EGEG).

2 Solution Method and Computational Experiments

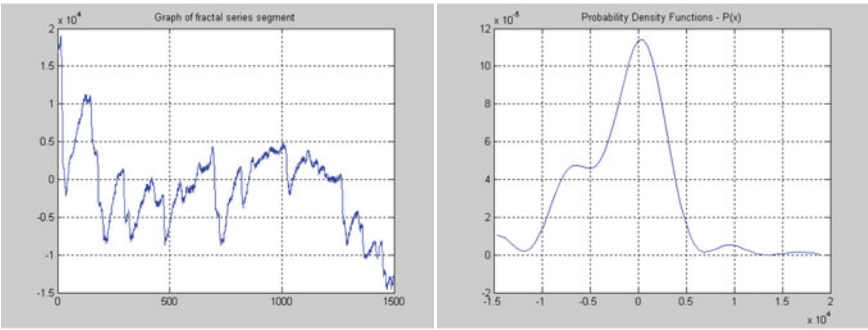
The authors of this chapter in [10] presented an experimental graph of the EGEG signal (clinical data), identified laws for distribution of local segments, and proposed a modification of the SSA method by reconstructing the evolution of the distribution laws for L-embedding vectors. The fast identification of distributions enables us to single out supporting components, reduce the trajectory matrix order and compress a fractal signal with no loss of relevant information. The data obtained may be used for urgent diagnosis and therapy.

The results of the stochastic analysis of the Hankel trajectory matrix (identified singular spectra) for a fractal time series are also described therein.

Furthermore, it is necessary to continue the study of the stability properties when identifying the distribution densities for singular values of large Hankel matrices. The study of the said process characteristics using the perturbation method is important for assessing the stability in case of measurement or calculation errors when solving nonlinear DE.

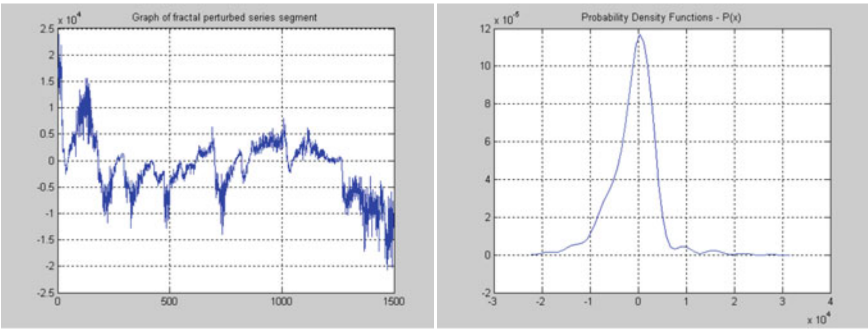
Figures 1, 2, and 3 show the results of the stochastic analysis (identification before and after the time series perturbation, the density of singular values) for a fractal EGEG signal.

Time series of 1500 samples and tractor matrices X sized [600 × 901] are considered for all three examples (EGEG signal, Wolf numbers, Chua's solution). Each member of the series has been perturbed by normally distributed random noise according to the formula $Xp = X_0 + \sigma X_0\ randn$, where Xp, X_0 are the disturbed and original signal sample, $\sigma = 0.30$ (*randn* is the program for generating a pseudo-random normal value: $\mu = 0$, $\sigma = 1$). The equivalent perturbation of all elements of the trajectory matrix respectively occurs therewith. This is quite a "strong" distortion of original signals and matrices.



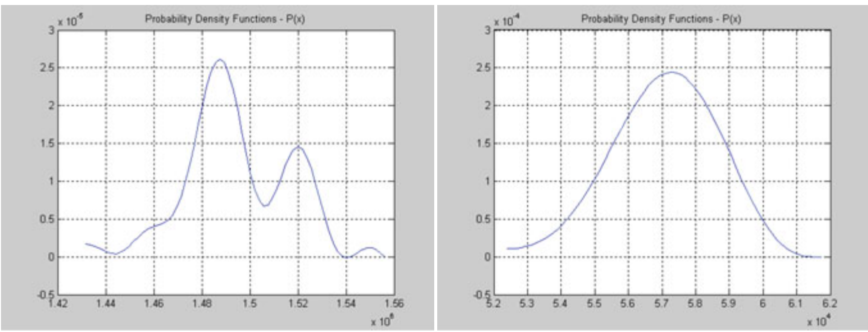
(a) **(b)**

Fig. 1 Graphs of the fractal series segment (1500 samples) and respectively identified density of the EGEG signal distribution–(**a**, **b**)



(a) **(b)**

Fig. 2 Graphs of the fractal perturbed series segment (1500 samples) and respectively identified distribution density of the EGEG signal–(**a**, **b**)



S1NOPT = 9 k = 1.874 t_e = 0.313 s

S100NOPT = 4 k = 2.041t_e = 0. 266 s

Fig. 3 Graphs of identified distribution densities of singular values numbered 1, 100 in a cycle of 100 disturbances of the EGEG signal by normal noise. NOPT is the optimum of expansion terms for P(x), k is the entropy coefficient, t_e is the identification time for P(x)

Figure 2 illustrates the resulting series (the EGEG signal plus random noise distributed according to Gaussian law) as well as the probability density thereof. A single perturbation adds a significant distortion to each sample of the useful process and this is reflected in the graph P(x)–(b).

Small singular values have increased through the perturbation by about 12 times having decreased the conditioning number of the perturbed matrix X by an order of magnitude. The identification time is 10 s.

Furthermore, the distributions of the singular values of Hankel matrices in a cycle of 100 perturbations have been identified. Thus, the degree of the stability of a fractal EGEG biosignal, a random series of Wolf numbers, and the chaotic solution of Chua's SDE to distortion by normal noise of a significant level is correctly estimated.

The identification of distributions of six hundred singular values in a cycle of 100 perturbations takes 12.7 min. Most of the time is spent on the 100-fold computation of the SVD decomposition (MATLAB program). Figure 3 shows graphs of two singular values and some distribution parameters. The detecting of bimodal distributions in the first singular values is quite an important circumstance in the conditions of the linear identification problem.

In general, the stochastic properties of the said fractal process are resistant to distortions by normal noise. The use of parallel computing algorithms will significantly reduce the time of analysis.

The second subsection contains some results of research in heliobiology. The creation of high-precision and up-to-date mathematical methods for identifying hidden rhythms from noisy arrays of biological and heliogeophysical data is an urgent task of fast-developing branches of space medicine, biophysics, and biomedicine [21–25].

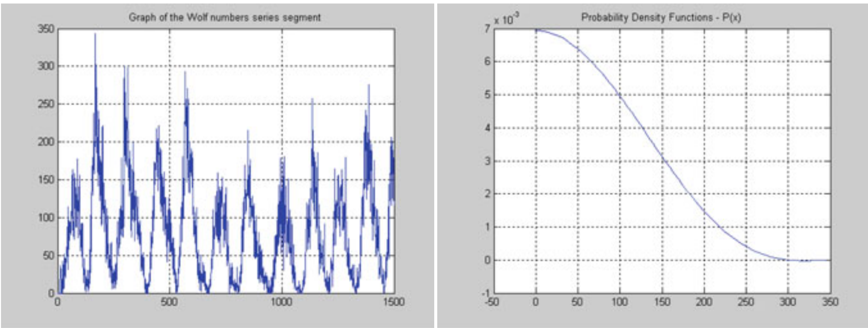
For this purpose, the stochastic analysis of the time non-stationary series of Wolf numbers from 1823 to 1948 is considered [26]. The series contains 1500 monthly average values. The results obtained from the identification of distributions of the trajectory matrix singular values for Wolf numbers are original and can be used as the basis for long-term forecasting of vital activities of terrestrial organisms depending on resonance periods of the solar activity.

The results of the stochastic analysis (identification, singular spectra and singular value densities) are shown for a series of monthly average Wolf numbers are shown in Figs. 4, 5, 6 and 7 below by analogy with the analysis of the EGEG signal. The application procedure and parameters in the perturbation method are the same as for a fractal signal. But the results are different: singular values with high numbers have only increased twofold.

The singular spectrum is more resistant to noise, notwithstanding that the degree of the series distortion is proportionally the same. The conditioning number of the matrix X (600,901) before and after the disturbance is 449 and 217, respectively. The computation time has not changed (10 s).

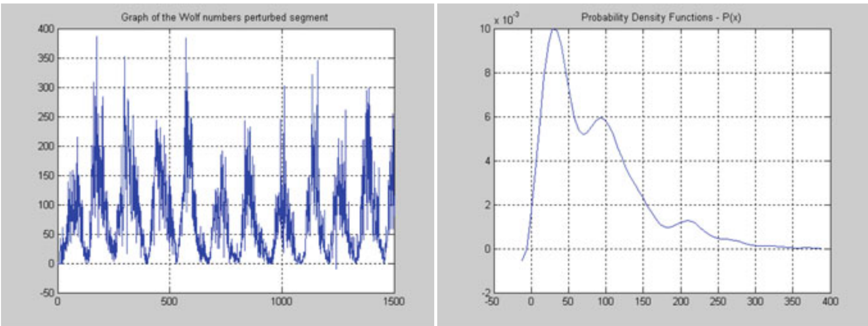
The identification of distributions of all 600 singular values in a cycle of 100 perturbations takes 13.2 min.

The preliminary conclusion is: a non-stationary series of Wolf numbers are resistant to distortion by noise with normal distribution. Additional information on the



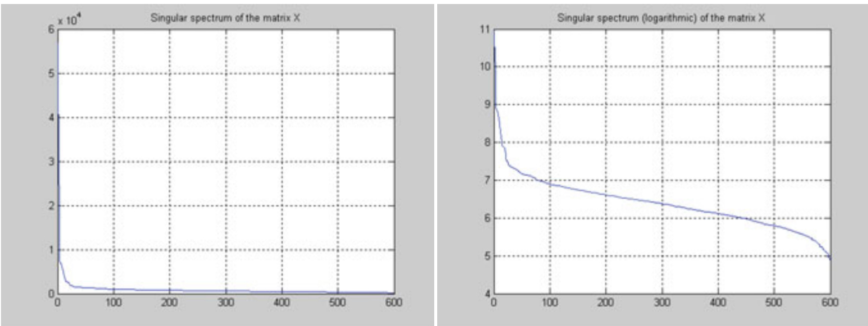
(a) **(b)**

Fig. 4 Graphs of the initial series segment (1500 samples) and respectively identified distribution density for the Wolf numbers series (**b**)



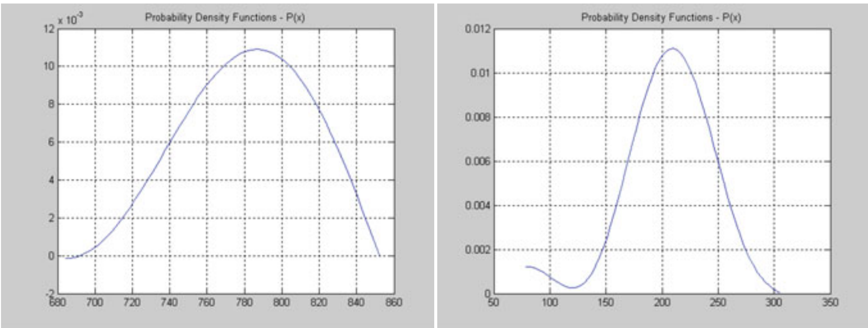
(a) **(b)**

Fig. 5 Graphs of the Wolf numbers perturbed segment (1500 samples) and respectively identified distribution density for the Wolf numbers series (**b**)



(a) **(b)**

Fig. 6 The singular spectrum of the trajectory Hankel matrix X(600,901) for Wolf numbers–(**a**), the same graph on a logarithmic scale–(**b**)



(a) **(b)**

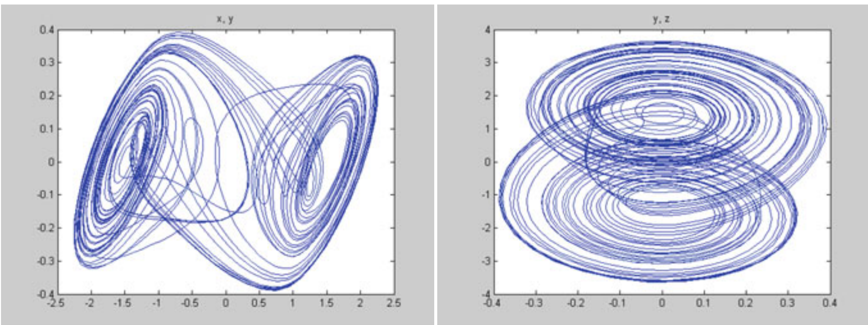
S400 NOPT = 2k = 1.998t_e = 0.234s S600NOPT = 4 k = 1.946 t_e = 0. 235s

Fig. 7 Graphs of identified distribution densities for singular values numbered 400 and 600 in a cycle of 100 disturbances of Wolf numbers by normal noise. NOPT is the optimum of expansion terms for P(x), k is the entropy coefficient, t_e is the identification time for P(x)

properties of this series can be obtained by using the SSA method with the separation of the trend, harmonic periodicals, and residuals–noise components. The analysis of the distribution of noise components is the most important for clarifying the stability of Wolf numbers retaining their stochastic characteristics.

It shall be noted that the methods elaborated by the project authors for identifying stationary and non-stationary processes enable to restore with high resolution the laws of distribution of any complexity with sample scopes up to 10,000 units and more.

The third analyzed time series represents a chaotic process–the x-component of the solution for the nonlinear SDE of the conventional Chua's circuit [13, 14]. Figure 8 illustrates two-phase portraits of Chua's solution components. The strange



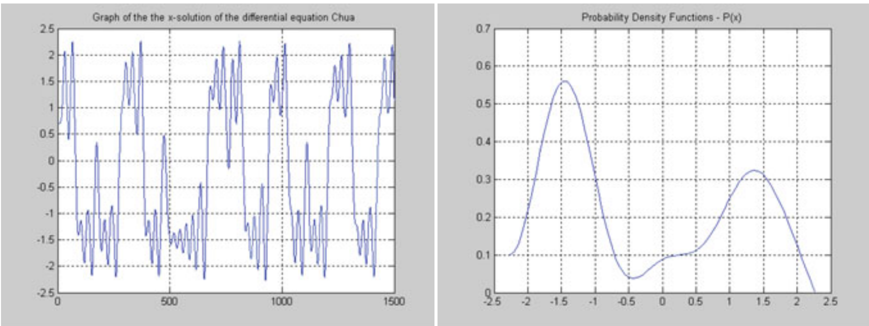
(a) **(b)**

Fig. 8 Phase portraits for solutions of the Chua's differential equations system attractor of the system consists of two centers of attraction and presents a very smooth configuration of trajectories.

A stochastic analysis is performed and some important results are shown as in the above two examples: a fractal signal and a non-stationary process (Figs. 9, 10 and 11).

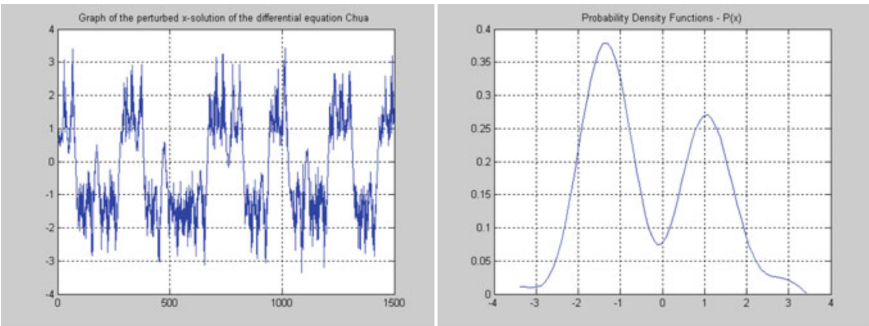
The identification of the bimodal distribution of one of the components in the chaotic solution for Chua's strange attractor shall be noted as an interesting feature. The other two components y and z have stable unimodal distribution densities within the selected sample size.

We will cite as an example a number of the "perturbed" singular values after the 100th iteration: 430.32; 427.26; 361.02; 345.6; 232.47, …, 2.87; 2.2933; 2.284; 2.0165; 1.9875 and note that the conditioning number has decreased by 194 times.



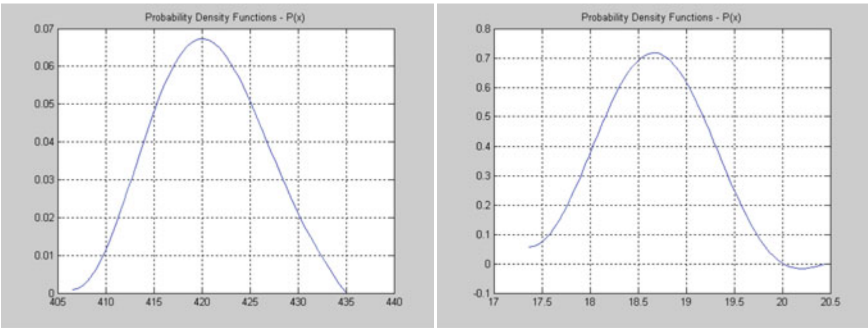
(a) (b)

Fig. 9 The initial series segment (1500 samples) and respectively identified distribution density for the x-solution of the Chua SDE



(a) (b)

Fig. 10 The perturbed series segment (1500 samples) and respectively identified distribution density for the x-solution of the Chua SDE



S1 NOPT = 3k = 2.031t_e = 0.235s S100NOPT = 3k = 2.030 t_e = 0. 266s

Fig. 11 Identified distribution densities for singular values numbered 1, 100 in a cycle of 100 disturbances of the x-solution of the Chua SDE with normal noise. NOPT is the optimum of expansion terms for P(x), k is the entropy coefficient, t_e is the identification time for P(x)

It proves the far greater dependence of the singular spectrum of the chaotic realization than in the other two examples. The complete implementation of the SSA method with the separation of additive components of Chua's x-solution with the distribution analysis is given below. Table 1 shows for illustration the initial fragment (10 × 10) of the Hankel trajectory matrix for the x-solution of the SDE of the Chua's contour.

The analysis of the evolution of embedding vectors for the trajectory matrix X (some local minor changes occur in the columns) enables us to consider the upgrading for the SSA method proposed by the authors to be effective to compress information and reduce the order of this matrix. The basis for the algorithm is the identification of distributions and the calculation of the Shannon entropy for L-vectors.

3 Decomposition of Time Series into Interpretable Additive Components

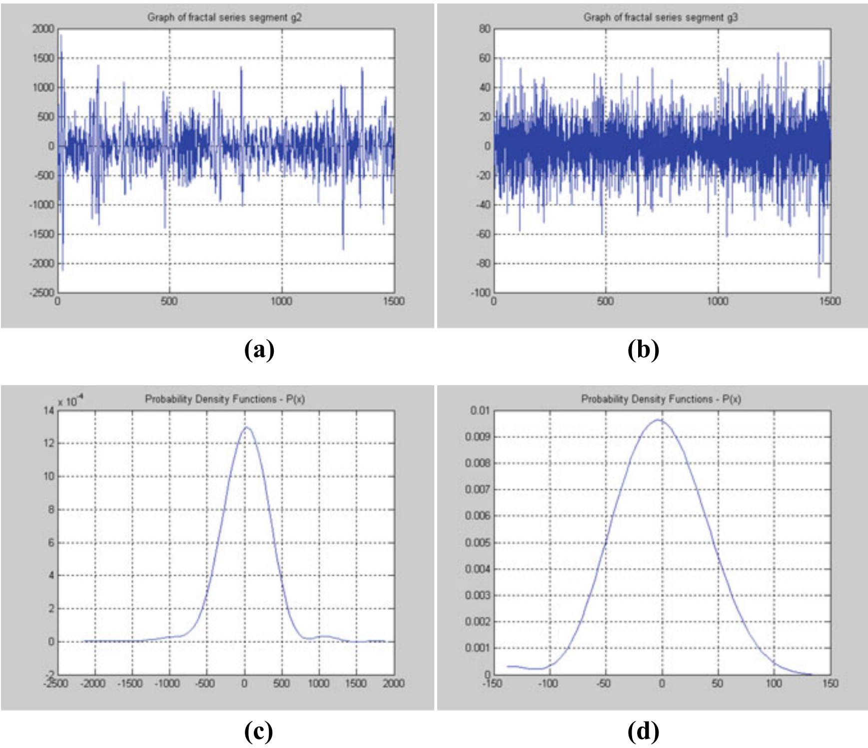
The third aspect of this chapter is the analysis of Hankel matrices of all three-time series using the SSA method with separating of relatively regular constituents and noise terms. As per algorithms of [18], we set the problem of decomposing each time series into a regular component and two different noise terms with different distribution laws. We will perform time series decomposition using a MATLAB program.

The results of the study have shown that under the conditions of complex fractal or chaotic random processes the conventional option of separation into trend, harmonics, and noise shall not always be successful.

Figure 12 shows the graphs of noise components and their distribution densities

Table 1 Fragment of the Hankel trajectory matrix for the Chua's SDE solution

	1	2	3	4	5	6	7	8	9	10
1	0.7	0.70011	0.70022	0.70034	0.70045	0.70101	0.70158	0.70214	0.70271	0.70558
2	0.70011	0.70022	0.70034	0.70045	0.70101	0.70158	0.70214	0.70271	0.70558	0.7085
3	0.70022	0.70034	0.70045	0.70101	0.70158	0.70214	0.70271	0.70558	0.7085	0.71146
4	0.70034	0.70045	0.70101	0.70158	0.70214	0.70271	0.70558	0.7085	0.71146	0.71447
5	0.70045	0.70101	0.70158	0.70214	0.70271	0.70558	0.7085	0.71146	0.71447	0.73025
6	0.70101	0.70158	0.70214	0.70271	0.70558	0.7085	0.71146	0.71447	0.73025	0.74725
7	0.70158	0.70214	0.70271	0.70558	0.7085	0.71146	0.71447	0.73025	0.74725	0.76551
8	0.70214	0.70271	0.70558	0.7085	0.71146	0.71447	0.73025	0.74725	0.76551	0.78506
9	0.70271	0.70558	0.7085	0.71146	0.71447	0.73025	0.74725	0.76551	0.78506	0.84685
10	0.70558	0.7085	0.71146	0.71447	0.73025	0.74725	0.76551	0.78506	0.84685	0.92143



NOPT = 10k = 1.968 NOPT = 5k = 2.054

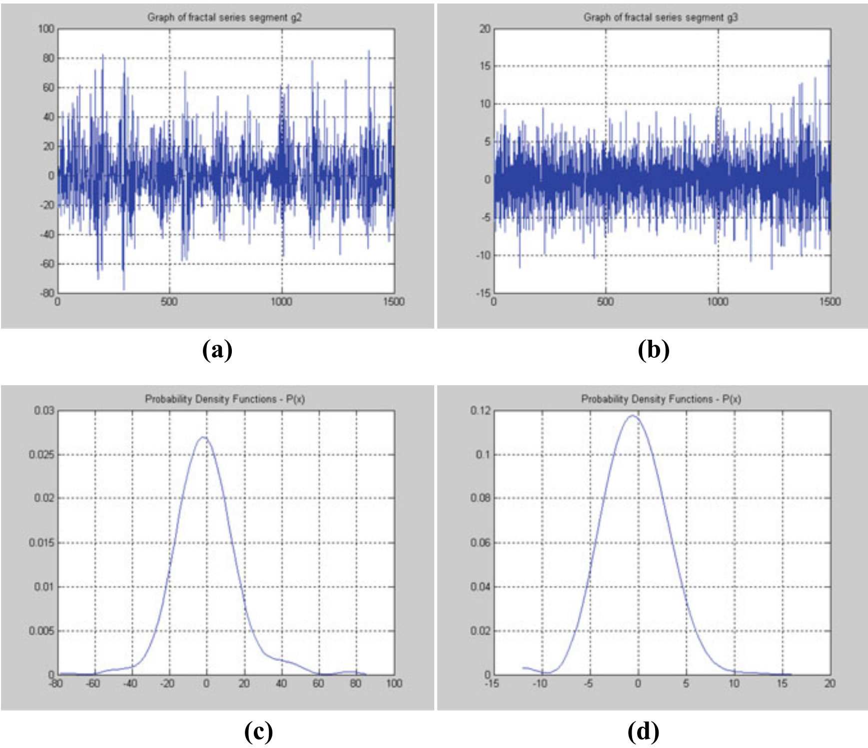
Fig. 12 EGEG-signal. Graphs for the separated first g2 (**a**) and second g3 (**b**) noise components and respectively identified distribution densities–(**c**) and (**d**). Nopt is the optimum of expansion terms for P(x), k is the entropy coefficient

for the EGEG signal identified by the author's method. We would like to note that this is the first time this approach has been implemented.

In addition to noise, a slightly smoother fractal regular component g1 consistent with Fig. 1 has been separated. The difficulties in identifying each component were determined by the scale of the Hankel matrix–540,600 elements and the computation time of 8.5 s.

Figure 13 shows similar results for the Wolf numbers series. Noise with different distribution densities was again obtained. Moreover, almost the Gaussian component (g3) was separated for the EGEG signal. The g2 components in both cases have steeper slopes of the distribution curves and are formed by a large number of trigonometric components.

The chaotic process expansion–the solution of Chua's SDE is of our main interest. In separation for the first two series as before the first 50 proper triplets were used for the first component and 400 subsequent proper triplets for the second component, for the third component- 150. The interpretation of the expansion shows that noise



NOPT = 9k = 1.973

NOPT =6k = 2.046

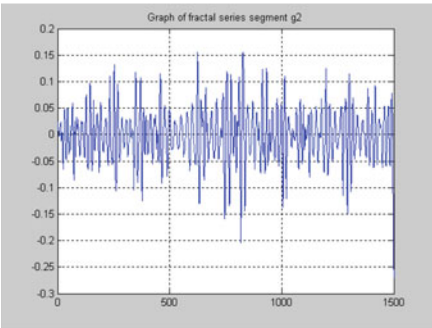
Fig. 13 Wolf numbers. Graphs for the separated first g2 (**a**) and second g3 (**b**) noise components and respectively identified distribution densities (**c**) and (**d**). Nopt is the optimum of expansion terms for P(x), k is the entropy coefficient

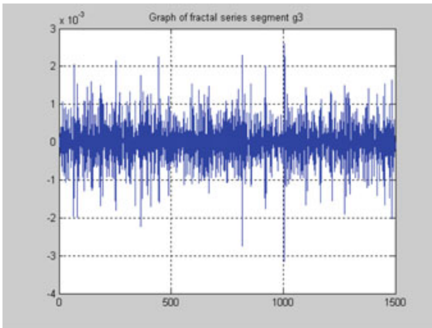
components while differing in amplitude just slightly differ in distribution densities. It shall be noted that if the regular component–g is nearly indistinguishable from the original signal, its distribution is distorted (Fig. 14e).

The identified feature of additive noise (close to normal) determines also the significant susceptibility to distortion of the Chua's SDE solution under introduced Gaussian noise (the graph of the perturbed phase portrait in Fig. 14f). The phase portrait of Chua's solutions (x, y) before the perturbation is shown in Fig. 8a.

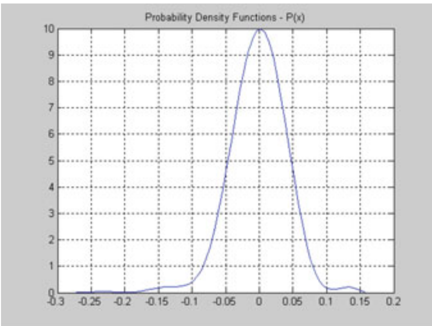
4 Results and Conclusions

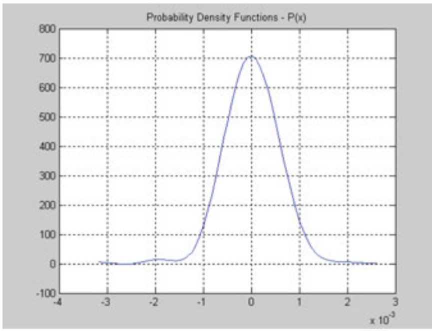
The identification of the distribution densities of singular values in the SVD expansion for Hankel trajectory matrices is carried out using the SSA method. The stochastic properties of matrix operators have been investigated for some important practical





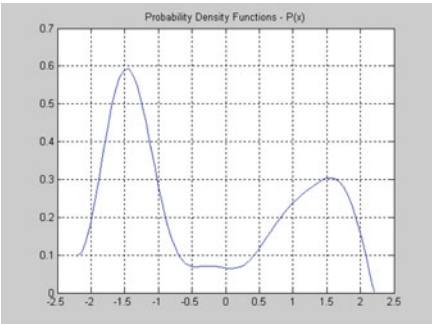
(a) **(b)**

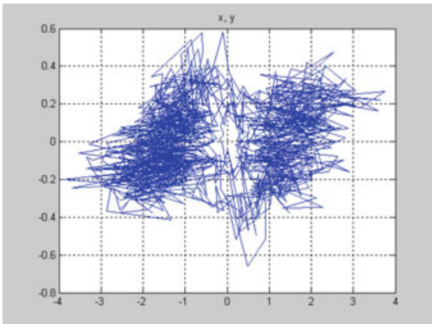




(c) **(d)**

NOPT = 8k = 1.994 NOPT = 8k = 2.020





(e) **(f)**

NOPT = 8k = 1.294

Fig. 14 Chua's Oscillator. Graphs of the separated first g2 (**a**) and second g3 (**b**) noise components and respectively identified distribution densities (**c**) and (**d**). The g1 distribution density is a regular chaotic component–(**e**). Phase portrait of the Chua's solutions (x, y) after perturbation by normal noise (**f**) problems in medicine and natural science: (1) the EGEG signal in gastroenterology; (2) time series of Wolf numbers for biomedical purposes; (3) chaotic processes–solutions of the Chua's system of differential equations as a potential nonlinear-inertial model of chaotic processes in the biology of living structures.

The degree of the stability of a fractal biosignal, a random series of Wolf numbers, and the chaotic Chua solution was assessed using the perturbation method to distortions by normal noise of a significant level (the simulation of measurement or calculation errors).

The possibilities of the developed methods are shown for identifying various probabilistic processes, which enable to reveal and restore with high resolution the laws of distribution with polymodal specificity. For illustration, the identification of the bimodal distribution of one of the components in the chaotic solution for Chua's strange attractor is noted.

The time series decomposition into interpretable additive components: regular components and noise with different distribution densities was performed using the SSA method. The instability of the Chua chaotic oscillations to noise with a normal distribution is shown.

The conducted studies are relevant for the creation of mathematical models of human body structures, organs, and systems displaying their stochastic and chaotic properties under extreme conditions, including during long-term space expeditions.

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Designing a Data Analysis Subsystem for Predicting the Properties of Antifungal Antibiotics

Eldar E. Musayev, Tamara Chistyakova, Vera A. Kolodyaznaya, and Valery V. Belakhov

Abstract In this chapter, we describe the algorithms for data processing applied as part of an intellectual analysis subsystem of a software system for predicting and researching the properties of antifungal antibiotics. These include models for predicting toxicity based on assays as well as acute oral toxicity. The mathematical models were trained, tested, and validated on different sets of antifungal antibiotic data. Testing showed the models' accuracy and viability for predicting antifungal antibiotics' properties.

Keywords Software development · Antifungal antibiotics · Mathematical models · Machine learning

1 Introduction

Fungal infections are one of the most important issues in healthcare. The number of fungal infections is growing as a result of, among other reasons, continuing environmental pollution, an increase in background radioactivity, improper application of broad-spectrum antibiotics, growing use of cytostatic and immunosuppressive drugs, and the appearance of more and more frequent antifungal drug resistance [1–3]. Among these infections, invasive mycoses are becoming a more and more important medical concern due to the growing number of immunocompromised patients [4–6]. The number of currently available and approved systemic antifungals is insufficient [7–9], and the progress of developing novel antifungal drugs is not fully proportional

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to the rate of growth of antifungal diseases, which include invasive fungal infections that are an existential and growing problem for modern healthcare [10–12]. Effective use of antifungal drugs to treat various mycoses is an important factor in the fight against antifungal infections.

One of the main issues affecting drug research is the cost of research and development, which can reach as high as 2.5 billion dollars [13]. The time it takes to develop a new drug is also a key issue, as a great deal of time is lost on drugs that ultimately do not pass pre-clinical or clinical trials.

One of the modern approaches to developing novel highly-effective low-toxicity antifungal drugs with improved medical, biological, and biopharmaceutical properties is the chemical modification of existing antifungal drugs, chief among those polyene macrolide antibiotics [14–16]. In this chapter, we discuss a specific class of antibiotics: polyene macrolide antibiotics (PMA), which make up approximately a quarter of all existing antifungal antibiotics. The chemical structure of a PMA consists of a macrolide ring that contains conjugated double bonds on one side (forming the lipophilic side of the molecule) and a number of hydroxyl and keto groups on the other (forming the hydrophilic side of the molecule). Their biological target is ergosterol, one of the components of a pathogenic fungi phospholipid membrane.

Amphotericin B is the drug of choice (gold standard) among all known PMA due to its high antifungal activity against the vast majority of known clinical forms of mycoses. PMA derivatives (PMAD) are chemically modified versions of existing PMA drugs which retain the biological activity of the initial drug while having lower toxicity. They can be an important topic of research in the fight against fungal drug resistance [17–19].

Software engineers can support the process of PMAD research by creating a software system that can predict antifungal activity and toxicity on the basis of the chemical structure of a molecule.

The goal is the development of models and a software solution providing those models that can reduce antifungal drug research time and cost by selecting such PMAD that have lower toxicity while retaining their ability to bind to the biological target. Using such a program, a researcher can check the toxicity and antifungal activity of a potential PMAD, and select such PMAD to go to pre-clinical trials that have more favorable traits. The program helps to cut time and other resource expenditure for pre-clinical and clinical trials of PMAD that lack the desired pharmaceutical properties.

2 Description of the Software System

The software system contains interfaces for researchers, experts, and database administrators. It includes an intelligent data analysis subsystem, a subsystem of synthesis step selection, and databases providing them with the data they require to function (see Fig. 1).

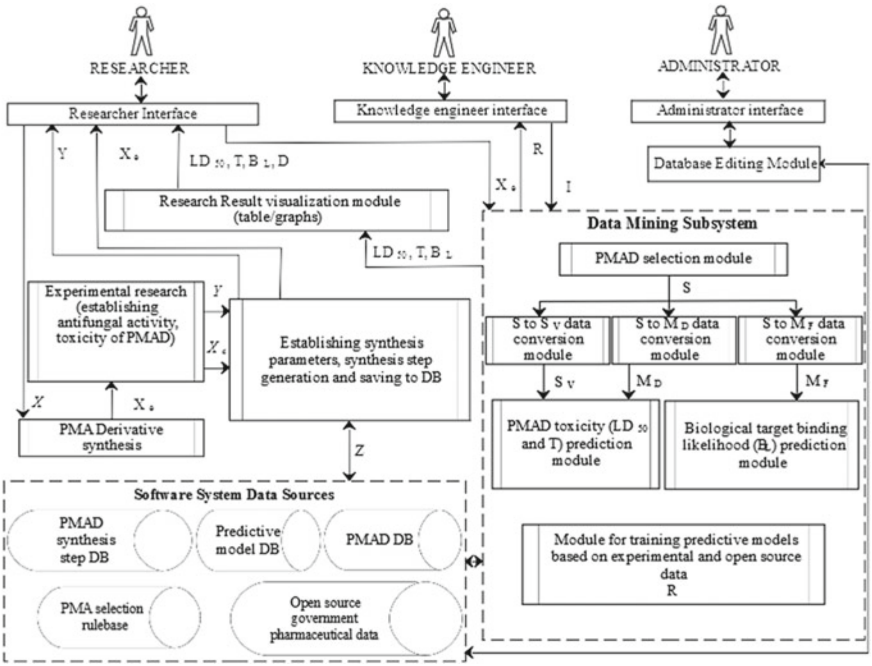

Fig. 1 Architecture of the software system for predicting and researching antifungal antibiotics' properties

Where LD50—the lethal dose for half of the population (mg drug/kg, oral intake, rats), T—a vector of predicted results of assays corresponding to toxicity signaling reactions, BL—the likelihood of binding to the biological target (%), D—the graph representation of the molecule, I—additional data to train the neural networks on, R—the results of this training process (AUC, MSE), S—the SMILES notation representation of the molecule's structure, SV—a vectorized version of that notation, MD—a vector of molecular descriptor values generated from the SMILES notation representation, MF—Morgan's molecular fingerprint bit vector for the molecule, X—description of the initial PMA, Xe—the result of modifying the structure of that PMA to create a PMAD, Y—the experimentally derived values acquired by testing that PMAD, and Z—the PMAD synthesis steps.

The data analysis subsystem consists of one acute toxicity model based on gradient boosted decision trees, 12 recurrent neural networks modeling one property each based on embedded vector representations of the elements of the SMILES notation of the molecule, and a deterministic algorithm for predicting biological activity based on pharmacophore filtering.

3 Data Analysis Subsystem Components

The acute toxicity model utilizes the gradient boosted decision tree model catboost in order to predict toxicity. It is trained on data retrieved from ChemIdPlus [20] in the form of tsv data (approximately 6000 values). Of note is that, prior to predicting the value, we multiply it by a normalized (0, 1] value of its logP in order to adjust somewhat for absorption differences due to lipophilicity. The data is input as a SMILES string, then processed using RDKit [21], which also provides us with the descriptors we use and the RDKit molecular fingerprint that also serves as input. The data is then fed into a gradient-boosted decision tree (catboost) model. The model's hyperparameters are as follows: iterations: 50,000, depth: 6, od_type: 'Iter', od_wait: 500, learning_rate: 0.07, random_strength: 40, l2_leaf_reg: 100, rsm: 0.3.

The predicted values are divided by the normalized logP value. The normalizer model is stored alongside the catboost model.

The assay-based toxicity prediction has a pre-processing step. First, we use the Chembl database [22] to attain approximately 1.7 million SMILES representations of valid molecules. We then determine all of the unique elements the SMILES notation consists of and one-hot encode them. We then utilize a skip-gram variant of word embeddings on these elements. The window size is 11 (5 to each side of the predicted element) and the embedded vector has 15 elements. The skip-gram variant of neural network encoding for embedded vector attainment is presented in Fig. 2.

We limit predictions to SMILES notations of at most 300 elements. If a SMILES notation is shorter than 300 elements, we append zero vectors to ensure all inputs are of identical (300, 15) shape. The utilized neural network consists of a bi-directional GRU layer, represented in Fig. 3. The network is trained on the tox21 dataset [23].

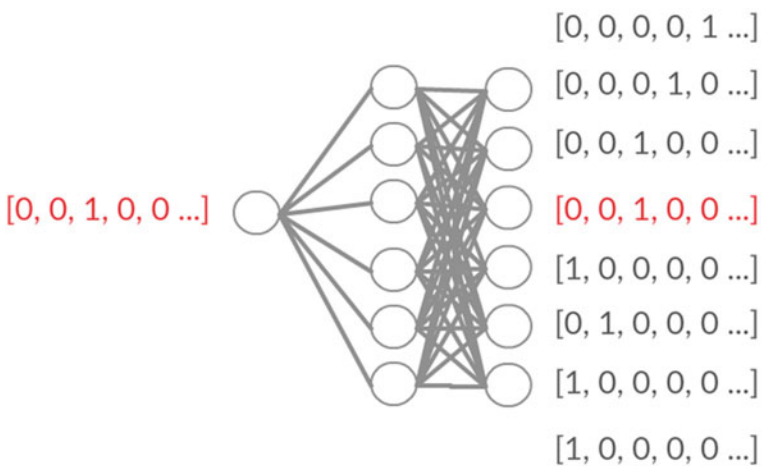

Fig. 2 Skip-gram encoding to attain an information-rich embedded vector (represented here as the hidden layer)

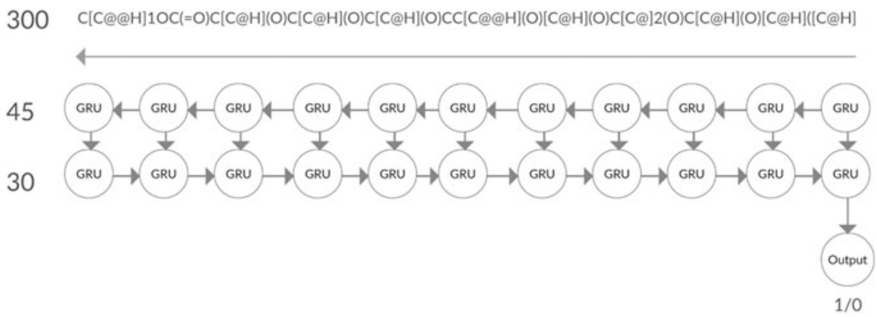

Fig. 3 Representation of a bi-directional GRU model for predicting one assay-based toxicity indicator. The figure represents the SMILES notation in its character form, though in the actual input each element is replaced by its embedded vector

The biological activity pharmacophore filtering model is a deterministic algorithm. First, RDKit fingerprints of a subset of polyene macrolide antifungal antibiotics are generated. Then, these are combined into a single fingerprint in such a way that only those features that exist in each of them are left in the resulting pharmacophore. This new fingerprint is treated as the minimum set of features required for antifungal activity. The algorithm to predict the probability of antifungal activity is as follows:

$$p = (\Sigma 2048_i = 1\ M_i * PH_i)/(\Sigma 2048_i = 1\ PH_i),$$

where p—the predicted value, [0, 1], corresponding to the probability that the input molecule will show antifungal activity;

Mi—the i-th value of the 2048-bit vector, corresponding to the presence or absence of a structural element of the researched molecule;

PH_i—the i-th value in the 2048-bit vector, corresponding to the presence or absence of a structural element of the pharmacophore;

In order to use this algorithm to classify researched molecules as having or lacking antifungal activity, a cutoff value is used. The selected cutoff value is 0.95, meaning that 95% of all structural elements of the pharmacophore must be present in any researched molecule for it to be marked as an antifungal antibiotic.

4 Interpretation and Discussion of Research Results

The acute toxicity model's root means squared error was 58 mg/kg (LD50, oral intake, rats). This was acceptable given that the molar weight of antifungal antibiotics tends to be 600+ g/mol. The assay-based toxicity prediction utilizing the tox21 dataset results is presented in Table 1.

Table 1 Tox21 modeling results

Assay	AUC	f-1
NR-AR	0.783569	0.969507
NR-AR-LBD	0.84447	0.981438
NR-AhR	0.88377	0.938144
NR-aromatase	0.799273	0.954627
NR-ER	0.715153	0.875431
NR-ER-LBD	0.826407	0.953131
NR-PPAR-gamma	0.767862	0.96973
SR-ARE	0.864636	0.888909
SR-ATAD5	0.859089	0.974173
SR-HSE	0.870134	0.969882
SR-MMP	0.912109	0.91518
SR-p53	0.854033	0.967989

The biological activity prediction pharmacophore filter was tested on a set of antifungal antibiotics as well as a set of drugs that are not antifungal antibiotics. With the selected cutoff point of 0.95, all of the antifungal antibiotics were correctly classified as such, and none of the non-antifungal drugs were classified as antifungal drugs.

5 Conclusion

We proposed an approach to designing a data analysis subsystem for a software system for predicting and researching the properties of antifungal antibiotics. These include gradient-boosted decision tree models, recurrent neural networks, and non-statistical algorithms. The software solution is configurable to various types of antifungal antibiotics, and its models can be trained on more antifungal antibiotic derivatives data to improve their accuracy. Testing was performed using sets of existing antifungal antibiotics as well as a number of recently synthesized novel antibiotics [14–16, 18, 19]. Testing supports the applicability of the system for predicting antifungal antibiotics' properties.

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Digital Technology in the Development of Healthy Diet Decision Support System

Marina Nikitina

Abstract The chapter presents a computer system in the assessment of a healthy diet. Based on mathematical models, the system provides a solution of structural-parametric optimization problems including a variety of constraints and conditions, followed by the choice of the optimal solution for the given utility functions. The information basis of the system is a database containing nine independent tables. Each table contains 15 fields. The structured query language (SQL) is used. An aggregate algorithm for implementing the solution of healthy diet composition, containing 4 stages, with due consideration for a "human health passport" is described. At the first stage, based on anthropometric data and biomarkers (hemogram, acidity of gastrointestinal tract) of a person's physiological state, the system generates a user model ("a human health passport"). The model considers the risk of disease and the gastrointestinal tract status. At the second stage, the system allows one to make a choice of food products based upon the physiological state of a person and proactively exclude "undesirable" food products, dishes, and culinary products. At the third stage, the developed diet is assessed, and the food nutrients (proteins, fats, carbohydrates, vitamins, macro- and microelements) the human body is fed with, are analyzed and compared with the recommended norms for this particular person. At the fourth stage, the adequacy of the diet is assessed according to the quality function.

Keywords Healthy diet · Structural-parametric optimization · Utility function · Computer system

1 Introduction

At present, it still remains one of the urgent problems to maintain human health, level out the risk of diseases, and thereby increase an active life expectancy [1–3]. We remember the quote from Hippocrates "Let food be thy medicine and medicine

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be thy food." In Russia, in 2019, according to the Federal State Statistics Service, the percentage of main causes of mortality was distributed as follows: 53%—circulatory diseases; 19%—neoplastic diseases, 12% other diseases (diseases of nervous and endocrine systems, diet disorders and metabolic disorders); 8%—due to external reasons; 5%—diseases of the digestive system; 3%—respiratory diseases.

An optimal diet, balanced in all nutrients and energy parameters contributes to (a) normal growth, weight, and development of children and adolescents; (b) prevention (leveling out) of diseases; (c) prolongation of a healthy and active life; (d) increased physical and mental performance; (e) increased tolerance to stress; (f) adequate adaptation to the environment.

An optimal diet is responsible for human health, with regard for all individual physiological needs. Designing an individual balanced diet considering many factors (individual intolerance to some components, anthropometric indicators, body mass index, indicators of nutritional and biological value) is impossible without the use of a mathematical tool [4–10] and modern digital techniques [11–15].

First of all, this is the use of Big Data (big arrays of information and knowledge about the subject area) [16, 17]. Our Big Data should contain information about dietary menus, functional and specialized products, nutritional characteristics of differentiated groups of people (students, pregnant women, retirees, etc.), norms of food nutrient consumption as per the region of residence, climatic zones, gender factors, anthropometric indicators (age, weight, body mass index), general and specific medical and biological requirements, characteristics of food consumption (whether there is an allergy or not), as well as information about the source of immune status disorders. It is also necessary to consider the combinability of foods in one diet, and various effects of the combination, such as synergy and antagonism.

In Russia, in 2018, the Resolution of the Presidium of the Russian Academy of Sciences No. 178 "On current problems of optimizing the nutrition of the Russian population: the role of science" was adopted. Paragraph 11 notes that the time has come to develop a new discipline "digital nutritional science", the creation of computer programs for the development of personalized recommendations for optimum nutrition.

The aim of this work is to develop a methodology and a computer system for assessing the quality of dietary structures for differentiated groups of the population, as well as a specific person.

2 Information Techniques for Optimizing Adequate Personalized Human Nutrition

2.1 Mathematical Model and Algorithm for Structural Optimization of the Diet

Mathematical model adjusted for the individual taste preferences of a person, with the prescriptions of a nutritionist, is as follows:

$$\sum_{k}\left(D_{kp}+D_{kd}\right)\delta_{k}\rightarrow max \tag{1}$$

where Dkp is a composed function value for "taste" preference of the k-th dish consumer; Dkd is a composed function value for "medicative" preference of the k-th dish; k is a logic variable for a component to be included in a dish or diet with restrictions allowing for [18]: non-repeatability of dishes in the daily diet, patient's financial capability, the k-th dish weight, maximum permissible caloric intake for breakfast, lunch and dinner, not-to-exceed amount of food for breakfast, lunch and dinner, permissible content of the i-th chemical element.

The algorithm for structural optimization of a diet is described in [19]. The essence of the algorithm is as follows. Following the analysis of all food nutrients, the k-th element is found, introducing the greatest (smallest) misbalance in the diet. Then the k-th element is minimized (maximized) taking into account its restrictions. If the k-th element deficiency is found, then the volume (serving) of one of the products with the maximum specific content of the insufficient (deficient) element is increased up to the highest level. Simultaneously, the volume (serving) of the product with the minimum specific content of the k-th element is reduced to the lower level. In case the k-th element excess is found, then the structural shift procedure is vice versa. The process is repeated until a deviation within the permissible range of the k-th element content in optimum balanced dietary structure is reached.

2.2 Composed Function of the Dietary Structure Quality

The quality and sufficiency of the dietary structure are determined, first of all, by its compliance with the requirements for the physiological characteristics of the body and the recommended norms for the biochemical elements' consumption. To assess the sufficiency and quality of the daily ration, a composed function is proposed [20], reflecting the weighted average total deviation of the state parameters from actual to normative values. With regard to the weight coefficients and defining certain groups of factors, the quality functional looks like:

$$F(x) = 1 - \sqrt{\frac{1}{n}\sum_{i=1}^{n} a_i \sum_{i=1}^{n_i} b_{ij}\left(\frac{x_{ij} - x_{ij}^0}{\Delta x_{ij}^k}\right)} \quad (2)$$

where n is the number of combined indicators;

x_{ij}, x_{ij}^0 are actual and required values;
Δx_{ij}^k is maximum deviation from the required value for the k-th quality level;
b_{ij} is weight coefficient of the j-th parameter in the i-th group;
a_i is group significance factor.

The quality functional value range is presented in form of the following graduated scale. If the quality functional value is equal to 1, this means complete coincidence of food nutrients and energy with the recommended ones, i.e. the best quality is achieved. If the quality functional value is equal to 0 or takes negative values—the recommended values are not achieved, that is the diet does not meet the specified quality level.

To determine weight coefficients, the complete factorial experiment can be used, where the following values are entered into columns of the response function yrk of the r-th repetition in the k-th experiment: 1–0.7—when the product is classified as having a very good level of quality; 0.7–0.3—good; 0.3–0—satisfactory; 0–(−0.2)—bad; less (−0.2)—very poor quality level.

3 Information Basis of the System

The information basis of the system is a database with nine independent tables. These tables correspond to different types of dishes, namely: "zakuska" (snacks), "sladost" (desserts), "hleb" (baked goods), "napitok" (drinks), "kasha" (cereals), "salat" (salads and vinaigrettes), "sup" (first courses), "myasoriba" (main courses, meat and fish dishes), "garner" (side dishes) (see Fig. 1).

Each table contains 15 fields. Id field contains a simple index, which is used to retrieve the required record from the database. The "bludo" fields contain the names of various dishes the user can select from the drop-down list. Next are the fields with physicochemical indicators of dishes per 100 g: "gir" (the field contains the fat content in the dish), "belki" (proteins), "uglevod" (carbohydrates), "cennost" (energy value of the dish), "C" (vitamin C), "B2" (vitamin B2), "B1" (vitamin B1), "PP" (vitamin PP), "E" (vitamin E), "Ca" (calcium), "Fe" (iron), "P" (phosphorus), "Mg" (magnesium) (see Fig. 2).

Each dish is given a specific record.

Fig. 1 Names of database tables

Fig. 2 Description of database fields

Field	Type
id	int(11)
bludo	varchar(400)
gir	float
belki	float
uglevod	float
cennost	float
C	float
B2	float
B1	float
PP	float
E	float
Ca	float
Fe	float
P	float
Mg	float

4 Work Within the System

Working with a computer system can be represented as an aggregate block diagram (see Fig. 3). At the first stage, based on anthropometric data and biomarkers (hemogram, acidity of gastrointestinal tract) of the person's physiological state, a user model ("a human health passport") is generated in the system. The model considers the risk of disease and the gastrointestinal tract status. The model description includes such descriptors as individual nutritional needs, biomedical requirements, dietary habits, available allergies.

At the second stage, the system allows one to make a choice of products considering the person's physiological state (see Fig. 4). For example, if a person has celiac disease, then products, dishes, and culinary products containing gluten are automatically excluded from his menu.

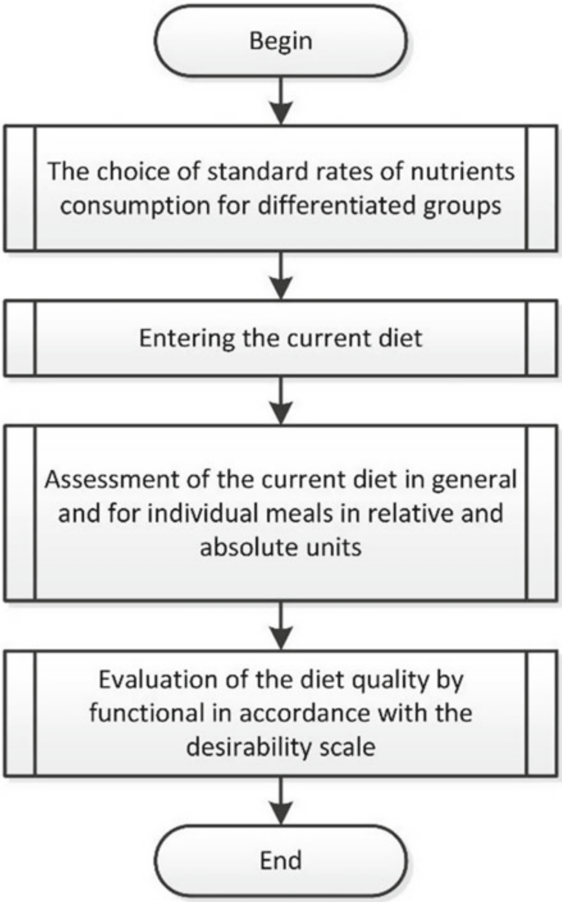

Fig. 3 An aggregate block diagram of a healthy diet based upon a person's "health passport"

Fig. 4 Selection of culinary products, dishes and products in "Breakfast" category

At the third stage, the developed diet is assessed, and the food nutrients (proteins, fats, carbohydrates, vitamins, macro-, and microelements) the human body is fed with, are analyzed and compared with the recommended norms for this particular person (see Fig. 5). The assessment is carried out for individual meals (breakfast,

Breakfast

		Yield, g	Proteins, g.	Fat, g.	Carbo-hydrates, g.	Energy value, kcal	C, mg	B2, mg.	B1, mg.	PP, mg.	E, mg.	CA, mg.	Fe, mg.	P, mg.	Mg, mg.
Boiled egg		70	8.05	8.925	0.525	110.25	0.14	0.315	0.126	0.35	1.05	38.5	1.351	336	21
'Magdalena' cake		60	3.27	14.346	31.452	236.184	21.27	0.456	0	0	0	0	0	0	0
Doctor's crispbread		60	1.56	4.92	27.78	145.2	0	0.03	0.096	1.98	1.02	10.2	0.84	51.6	21.6
Plain black coffee		200	0.1	0.4	0.4	14	0	0	0	1.2	0	10	0	14	0
"Health" Muesli Pear (25% of nuts and fruits)		50	4.3	1.75	32	133	28.515	0.055	0.12	0	0.3	33	0	0	45
Total for breakfast			17.28	30.341	92.157	638.634	49.925	0.856	0.342	3.53	2.37	91.7	2.191	401.6	87.6
As a percentage of the recommended daily ration	Young men		15.29	29.46	20.43	19.35	62.41	42.8	21.38	17.65	23.7	11.46	21.91	33.47	21.9
	Girls		18	33.71	24.06	22.81	62.41	57.07	26.31	19.61	29.63	11.46	12.17	40.16	21.9

Fig. 5 Estimated indicators of food nutrients for "Breakfast"

lunch, dinner) and the whole diet during the day in absolute and relative units.

As we can see in Fig. 5, the first column displays the names of selected dishes, culinary and food products; the second column indicates the weight of the serving. This is the data the user enters at the second stage when he/she make up his/her diet based on his/her preferences. The remaining columns display physical and chemical indicators calculated by the system. All indicators are presented at three levels.

The first level: calculation of indicators for each dish, culinary product, and food product separately;

The second level: calculation of complex indicators for breakfast, lunch, and dinner in general;

The third level: calculation of daily outcome indicators.

In addition to summarizing the overall results (see Fig. 5), the system compares the indicators with the recommended daily rates as a percentage.

At the fourth stage, the composed function of quality is calculated. If the obtained value of the quality functional corresponds to the acceptable level of the desirability scale, then the user receives his/her daily ration with differentiation in time and recommendations for food intake. Otherwise, if the diet does not meet physiological needs, then a return to the second stage to adjust the diet is made. And there is taking place a replacement of products. A detailed block diagram of the algorithm proposed product replacement is shown in Fig. 6.

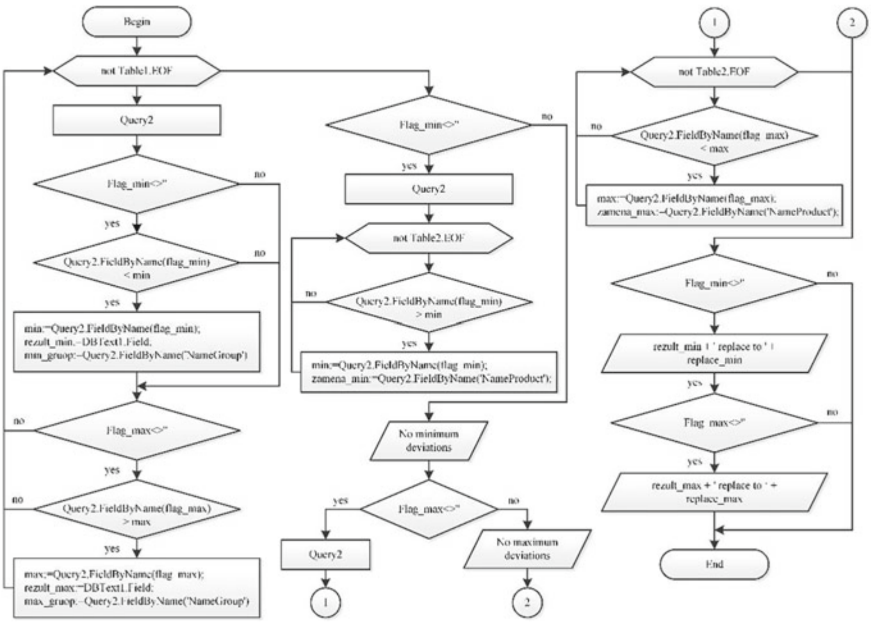

Fig. 6 Block diagram of the algorithm proposed product replacement

5 Conclusion

The developed computer system based on mathematical models provides the solution of structural-parametric optimization problems adjusted for a variety of constraints and conditions, followed by the choice of the optimum solution for the given utility functions. It (1) is easy to use, allows one to assess the daily diet quickly and reliably; (2) establishes an imbalance (excess/deficiency) of nutrients in the diet. The knowledge available in the system builds a cause-and-effect relation "If there is a shortage or excess of this or that food nutrient in the body, then this will lead to such and such a disease." The dietary structure (diet) is a health factor that can be changed easily to improve one's health.

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Pupillogram Acquisition and Analysis Technology for Human Functional State Assessing

A. M. Akhmetvaleev, M. Yu Danilchyk, A. S. Katasev, and I. V. Akhmetvaleeva

Abstract The technology of obtaining and analyzing pupillograms for assessing the functional state of a human-based on computer vision methods and neural network modeling is proposed. The obtained pupillograms, as the initial data for the analysis, have a stable shape with a minimum amount of noise, emissions, and missing values. The possibility of pupillograms analyzing and classifying based on convolutional neural networks is shown, which makes it possible to reduce the dependence from the results of assessing the functional state of a human on the input data variability. The composition and an example of the developed software and hardware complex functioning for human functional state assessing based on the pupillograms analysis are shown. The pre-trained convolutional neural network ResNet18 was selected as an analysis tool. The resulting neural network model showed a high classifying ability, which indicates the possibility of its effective practical use for solving the problem of a human functional state assessing in various subject areas.

Keywords Pupillometry · Pupillogram · Human functional state · Computer vision · Neural network model

1 Introduction

Pupillometry, as a method of pupillary reaction analysis, is used in medicine to diagnose ophthalmic diseases, to identify violations of the functional, psychological and emotional states of a person [1–6]. Currently, due to the computer vision use, the idea of this method has found application in solving problems of transport and public safety, life safety, in marketing research, and many others [1–3, 6]. The process of obtaining initial data (pupillograms), reflecting the dynamics of changes in the size

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of the pupil to changes in illumination, is inextricably linked with the video recording of the human eye at the time of the pupillary reaction, as well as the search for the circles of the pupil and the iris of the eye.

At the same time, the spread of the pupillometric approach in a non-invasive and non-contact recording of the pupillary reaction is hindered by various technical (software and hardware) limitations associated with the difficulties in obtaining the initial data (pupillograms and the corresponding values of the parameters of pupil reactions) in conditions other than stationary medical diagnostics. In most cases, the pupillary reaction registration and analysis is a complex technical problem due to the transience, relatively small size of the observed object (pupil), and, as a rule, low detailing of the video image. This necessitates the use of various devices for rigid fixation and positioning of a person's gaze, as well as making conscious efforts to register images of the eyes (self-control over the direction of gaze, focusing on a video camera lens, etc.) and obtaining pupillograms [2, 3, 7, 8].

Many restrictions are also created due to outdated methods of computer vision used to detect specified objects in images, calculate their characteristics and generate initial data for analysis. The pupil and iris of the eye, which are two circles inside the eyeball, are used as objects in pupillometry. Most computer vision methods search for the contours of objects in areas of sharp changes in image saturation. In this case, the problem of object detection in most cases is solved by classical methods of searching for concentric circles, for example, Hough transform, FRST, etc. [5, 7–9], which are sensitive to noise, outliers, and changes in the values of image parameters, which can lead to a decrease in the quality of the initial data obtained for the analysis (pupillogram).

For example, using the Hough method can lead to errors in the iris and pupils localization. At the same time, most errors in the circle's selection are associated with the presence of eyelids and eyelashes that overlap the sought objects, as well as glare and noise in the images. These artifacts are the reason for the appearance of distortions during the pupillogram formation, which inevitably leads to errors in evaluating the values of its parameters.

Pupillogram obtained using classical image segmentation methods often contains incorrect values such as noise, outliers, and missing values. Their presence leads to the need to use smoothing filters. In this case, the loss of a part of the time series (pupillograms) properties that are important for the analysis and the inadequacy of mathematical models constructed on such data is possible.

Thus, the use of classical computer vision methods makes it difficult to use the pupillometric approach for the human functional state (FS) assessment in a wide range of tasks not related to laboratory studies. This actualizes the need to develop new technology for obtaining pupillograms, increasing their quality for subsequent intellectual analysis.

2 The Technology of Pupillograms Obtaining

Currently, convolutional neural networks (CNN) are becoming relevant for objects recognition and classification in images. Their popularity is due to the high quality of practical problems solving. Like any neural network [10–13], SNN requires a sufficient amount of data for training and testing, which is not always possible [1]. In this regard, it is advisable to use pre-trained CNN models based on publicly available frameworks, for example, based on Google's Mediapipe [14]. This framework supports various hardware platforms, has ready-made solutions for recognizing faces, eyes on a human face, and irises. The framework code is distributed under the Apache 2.0 license. Models are processed using the TensorFlow and TFLite machine learning frameworks. Using Mediapipe simplifies the development of pattern recognition applications and obtaining high-quality initial data for analysis.

This chapter proposes a technology for obtaining pupillograms based on the specified framework use. Figure 1 shows the main stages of this technology.

At the initial stage, the face is detected in the image using Mediapipe, the mesh is applied to the face for better visualization. At the second stage, the eye area is extracted, the iris size of the eye is calculated, and the binary mask is formed to subtract areas that are not the eyeball from the image. The third stage is used for the color spaces of the image preprocessing and transforming, noise normalizing and filtering, glare detecting and eliminating. At the fourth stage, using the FloodFill algorithm (filling), regions of uniform color located in the middle of the iris are selected, which leads to the connecting of the pupil pixels into one segment. This algorithm is often used in graphic editors to determine the areas that should be filled with a specific color. At the final stage, the area of the resulting segment is calculated, normalized relative to the size of the iris, according to the following formula:

$$S = S_{pupil}/S_{iris},$$

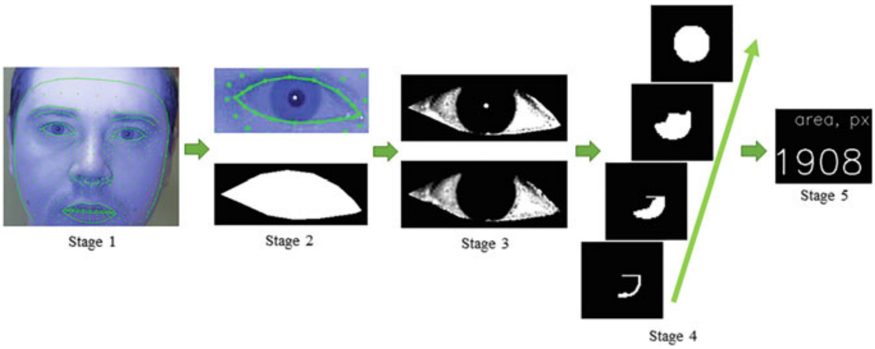

Fig. 1 The developed technology main stages diagram

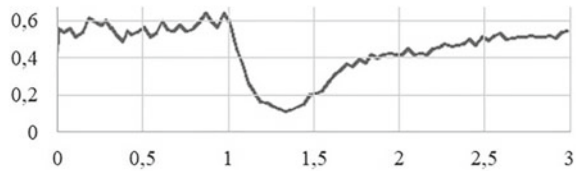

Fig. 2 Pupillogram obtained using the developed technology (abscissa—time in seconds, ordinate—the area of segment S)

where S_{pupil}—pupil area in pixels, S_{iris}—iris area in pixels.

Based on the calculated values, a pupillogram is formed, an example of which is shown in Fig. 2.

The resulting time series [15] is the desired pupillogram, on the basis of which it is possible to perform neural network modeling and the human functional state assessment [16]. As it can be seen from the figure, the pupillogram has a fairly stable shape, there are no outliers and missing values on it. The resulting pupillogram can be used for further processing based on the calculation of values and analysis of its parameters [1]. In addition, images of pupillograms can be used directly for classification based on the construction and use of CNN [1].

3 Pupillograms Analysis and Classification

In pupillometric diagnostics, the dynamics of changes in the size of the pupil is presented in the form of a pupillogram, which has characteristic parameters: the initial, minimum, and final diameter of the pupil, the diameter of the half-constriction, the latent time of the pupillary reaction, the time of half-constriction, expansion, etc. By analyzing the values of these parameters, it is customary to evaluate deviations in the human nervous system functioning [4, 17]. Different sets of the values of the pupillograms parameters are associated with certain functional states, for example, "norm" or "deviation from the norm".

Such a presentation of the initial data makes it possible to classify the set of the values of the pupillograms parameters by various methods of analysis [18–22]. So, for example, to assess the human functional state by the types of "norm" and "deviation from the norm", the methods of mathematical statistics and neural network analysis can be used. An example of an effective model for estimating the values of the pupillograms parameters is the model of a collective of neural networks. It is a combination of several neural networks of the same architecture, formed on the basis of the bootstrap method. However, the input parameters variability coming to the input of the collective of neural networks, caused by different filming conditions, equipment characteristics for video recording, delays in the hardware operation, leads to a decrease in the functional state assessing accuracy. Thus, the new effective methods development for pupillograms analysis is relevant to improve the classification accuracy.

Since the pupillogram is a two-dimensional image, it is possible to use convolutional neural networks to classify it. In this study, the pre-trained neural network model ResNet18 was used to assess the human functional state. It is capable of additional training on any class of images, including images of pupillograms.

This model consists of 20 layers. The first layer has 64 7×7 filters with a step of 2. Then there is a convolutional cascade of layers of 64, 128, 256, and 512 3×3 filters with a step of 2. There are two 3×3 sub-sampling layers in 2 steps with maximum value selection (Max Pooling) and average value selection (Avg Pooling). After the convolutional part, there is a fully connected layer, which has 512 neurons at the input and 2 neurons at the output. This layer is responsible for the human functional state assessment based on the values of features from the convolutional layer and has two classes: normal functional state and deviation functional state. All images of pupillograms passed the preliminary stage of normalization and were reduced to a size of 224×224 pixels, as required by the architecture of ResNet networks, and then transformed into a tensor format—a data structure used in convolutional neural networks.

4 Hardware and Software Complex for Human Functional State Assessing

To implement the proposed technology for obtaining, neural network analysis of pupillograms and assessing human functional state, a software and hardware complex (HSC) has been developed, shown in Fig. 3.

The hardware part of the complex is a combination of a video recording device (IR-sensitive video camera), an illumination source (infrared and white illumination), a computer for processing the results, and other peripheral equipment. This part of the HSC is a ready-made stationary solution with the possibility of transportation and deployment in any suitable premises in a short time.

The software part of the HSC consists of two main subprograms and implements the technology stages for obtaining pupillograms, neural network modeling based on the ResNet18 CNN, as well as conducting research and experiments. An example of the program's operation is shown in the following screenshot (see Fig. 4).

In the presented program window, visualization of the main stages of obtaining initial data is used, in particular: face detection and localization of the human eye area, search for iris and pupil circles, obtaining a peak pupil size, forming a pupillogram in the form of two-time series for each eye. In the process of the program's operation, its operator has given the opportunity of person's face accurately position, detail and focus the eye area, and a preliminary assessment of the pupillary response.

Fig. 3 General view of the hardware and software complex

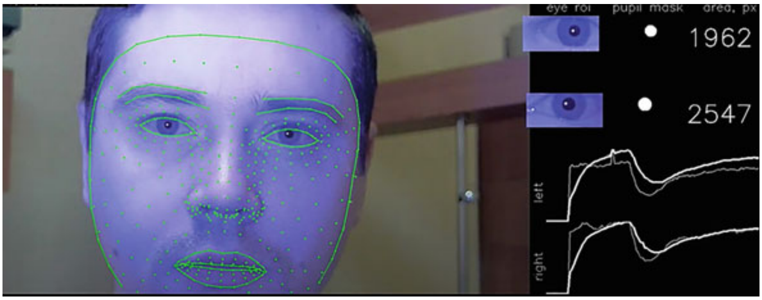

Fig. 4 An example of the program work of human functional state assessing

5 Research-Based on Software and Hardware Complex

To conduct research on the basis of the developed hardware-software complex, the functional state of human fatigue was used as the target functional state. The main assumption about finding a person in a state of fatigue was the presence of signs of psychoemotional and physical stress after a 24-h work shift in an organization that has an around-the-clock work schedule with a "day or two" shift schedule. Accordingly, before taking up the daily watch, a person must be in a normal functional state.

In the course of the research, initial data (images of pupillograms) were collected in a group of men and women, a total of 60 people, 25–35 years old, on duty around the clock with a break for rest of 3 h a day and subsequent rest for 48 h. The groups were divided by 20 people every day. Data collection was carried out within 3 days. Obtaining the initial data was implemented before taking over the daily watch and after the end of the 24-h shift for each person, during the period of the day from 8:00 to 8:30.

When collecting data, the same external conditions were provided: a room with the artificial light turned off, the windows were closed with translucent curtains, the person did not take medications that affect his central nervous system. A preliminary survey of their general condition was carried out in the subjects under study. When deviations in a human were detected that did not correspond to his target functional state, data collection was not carried out.

For each person, a data sample was formed, consisting of two pupillograms (one for each eye). To enrich the data, a repeated video recording of the pupillary reaction was carried out with a time interval of 10 min. Thus, for each person participating in the study, 8 pupillograms were obtained (4 for each functional state). In total, during the study, 480 pupillograms were obtained and analyzed, an example of which is shown in Fig. 5.

Figure 5a shows an example of a pupillogram of a person before starting the daily shift (normal functional state), and Fig. 5b—after the end of the 24 shift on duty (state of fatigue). The abscissa shows the frame numbers in the video image, and the ordinate shows the pupil size.

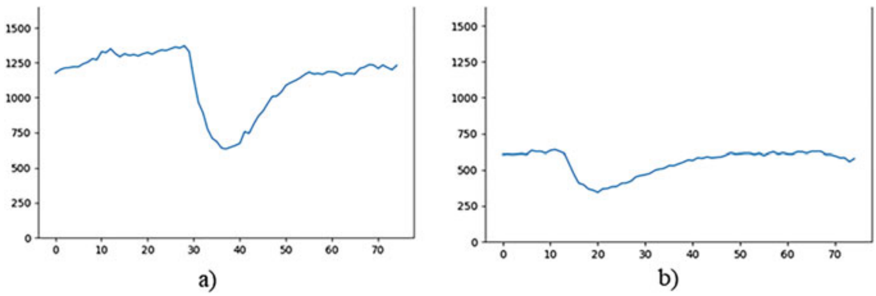

Fig. 5 An example of the obtained pupillograms

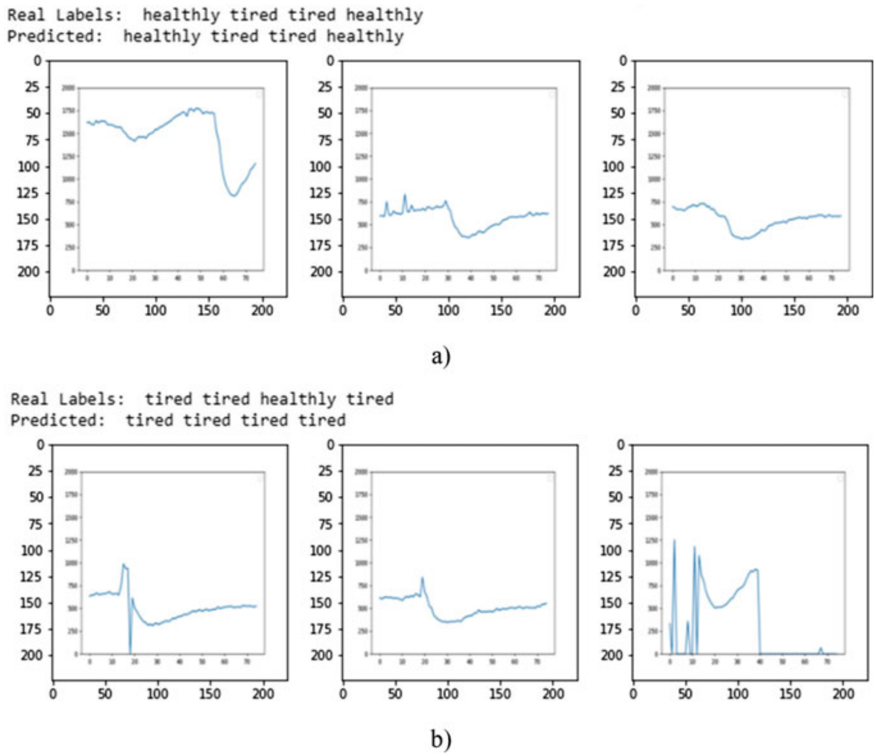

Fig. 6 Examples of successful (**a**) and erroneous (**b**) recognition of pupillograms

Examples of successful and erroneous recognition of pupillograms based on the proposed convolutional neural network model are shown in Fig. 6.

Figure (a) shows that the key elements of the pupillograms (slopes and rises of the time series), despite their obvious visual differences, caused, incl. differences in shooting conditions and delays during the operation of the HSC were successfully recognized and correctly evaluated by the neural network model. Figure (b) shows that the third pupillogram is incorrect due to a large number of gaps in it. Because of this, it was misidentified. This additionally actualizes the need for a pupillograms quality preliminary assessment and the automation of this process at the stage of the initial data preparation.

In addition, to compare and assess the accuracy of the results obtained, two models of the CNN were used, formed on two data sets obtained from the same initial video fragments, but using different technologies for their processing. The first set was obtained using classical computer vision methods, the second set is based on the iris and pupil circles manual marking, used to improve the accuracy and quality of the initial data, but requiring the use of additional time resources. To assess the constructed model's efficiency, the 1st and 2nd kind errors were used, as well as the overall classification accuracy.

Let class “1” be the human functional state of the type “deviation” (the case of positive examples), and class “0”—the human functional state of the type “norm” (the case of negative examples). In this case, the 1st kind of error occurs when the model incorrectly classifies the functional state of fatigue as a norm. Accordingly, the 2nd kind of error occurs when the normal human functional state is classified incorrectly.

The 1st kind of error was calculated using the following formula:

$$E_1 = \frac{n_1}{N_1} \times 100\%,$$

where n_1—number of positive examples rejected, N_1—the total number of examples in the testing sample.

The 2nd kind of error was calculated using the following formula:

$$E_2 = \frac{n_2}{N_2} \times 100\%,$$

where n_2—number of negative examples rejected, N_2—the total number of examples in the testing sample.

The results of 1st and 2nd type errors calculating, as well as the overall classification accuracy are presented in the following Table 1.

As it can be seen from the presented table, the CNN model (in comparison with other models) has a higher classification accuracy, and the number of 1st and 2nd kind errors, respectively, is less.

The results of the research showed that the developed CNN model has a better classifying ability in comparison with the collective of neural networks models. Taking into account that the models’ effectiveness assessment was carried out on validation data that are not part of the training and testing sample, we can count

Table 1 The constructed neural network models comparison

Criteria Model	Circles obtaining method (pupil boundaries)	1st kind errors (%)	2nd kind errors (%)	Classification accuracy (%)
NNT model No. 1	Computer vision based on segmentation methods	0,3	4,3	95,4
NNT model No. 1	Manual marking	0,3	3,1	96,6
CNN model	Computer vision based on the MediaPipe framework	0,2	2,8	97

on that the CNN model can effectively classification new data characterizing the functional state of human fatigue.

Thus, the proposed technology for initial data collecting and analyzing based on a convolutional neural network model can effectively solve the problem of the human functional state assessment.

6 Conclusion

The technology of obtaining pupillograms for neural network modeling and assessment of human functional state described in the work, as well as its software and hardware implementation, demonstrated the possibility of the more efficient and qualitatively new approach in solving various problems of pupillometric diagnostics. Elimination of various artifacts of time series through the use of modern methods of computer vision made it possible to improve the initial data quality, to preserve the time series properties necessary for analysis [15], and to ensure the stability of obtaining the dimensions of the eye circles in front of various artifacts in the images. In addition, the use of convolutional neural networks has led to the possibility of constructing new effective models for assessing the human functional state.

The developed CNN model for assessing the functional state of human fatigue can be widely used in various subject areas:

1. in the field of ensuring life safety for monitoring and assessing the state of personnel fatigue at workplaces, where the performance of certain types of activities is associated with an increased risk to human life and safety, as well as ensuring the functioning of various critical infrastructure;
2. in the field of transport security for monitoring the fatigue state of bus drivers, passenger aircraft pilots, etc., including through the introduction of pupillometry into the procedures of pre-trip medical examination as a decision making support system on admitting or removing a driver from driving motor transport if he has signs of fatigue [23];
3. to conduct various screening studies of a large number of people to identify deviations in their functional state.

Thus, the obtained results indicate the developed technology's effectiveness and its practical use possibility for constructing models for the human functional state assessing and solving a wide range of problems in various subject areas.

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Application of Integral Health Index in Evaluation of Efficiency of Rehabilitation of Children with Obesity

Olga Berestneva, Ivan Lyzin, and Nina Stepanenko

Abstract The purpose of the research: to study basic clinical and hormonal, metabolic, and psychological disturbances in children with obesity in various periods of the year. To evaluate the effectiveness of occupational therapy and identify the features of different systems of the body depending on the periods of the year based on calculation value of the integral indicator of health for children with obesity. In a survey of 298 children, of whom 200 people with obesity and 98 healthy children, month-to-month differences in the lipid and hormonal status of healthy children in the Siberian region were established, and clinical and laboratory characteristics of childhood obesity within a year were described. From December to July, in contrast to other months of the year, violations of psychoemotional status and decline in physical performance, improving lipid profile and proinflammatory cytokines were identified. Differentiated approach to the treatment of children with obesity, taking into account the monthly features of the main indicators of the clinical, hormonal, metabolic, and psychological status of these patients was substantiated.

Keywords Children · Obesity · Intervals of year · Treatment · Integral health indicator · Scaling · Pareto chart · Harrington function

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1 Introduction

Currently, there is an increased interest in the study of rhythmic processes in the body, both in normal conditions and in pathology. The study of biorhythms allows assessing the level of reactivity, functional state, and adaptive capabilities of the organism [1–3]. To this end, a large number of studies in the field of chronobiology of energy balance of the organism were made [4, 5], and the influence of seasonal changes in the environment on the functional state of organs and systems [6, 7], the level of physical performance, as the adaptive capacity and resistance of the organism, the effectiveness of medical, health [6, 7] and training [7–9] activities were examined. Despite this, the choice of a clear therapeutic approach, given the time period of the year in children with obesity in pediatric practice to date does not exist. Monthly study of metabolism indexes in healthy children and children with obesity may serve as a basis for the development of new approaches and methods of rehabilitation of pediatric patients with obesity and increase the effectiveness of therapy in the adverse timing of the annual cycle. For an objective assessment of the effectiveness of treatment of a large number of recorded parameters for each patient, one must select the most informative indexes, providing the greatest contribution to treatment outcomes. The development of an individual integrated indicator of the health of children with obesity at the were proposed stage of medical rehabilitation for this purpose.

2 Research Methods

In accordance with the intended purpose, a research strategy was developed. It included a monthly study of lipid and hormonal status in healthy children and obese children during the year and an evaluation of the effectiveness of the standard complex of restorative treatment.

Patients. In accordance with the goal and objectives, the clinical study of 298 children was conducted. They included 200 patients (100 boys and 100 girls), which were obese of I-III degrees aged 10–15 years (of 12.9 $\pm$ 1.5 years), and 98 children of a similar age (12,8 $\pm$ 0,1 years) were almost healthy (40 boys and 58 girls). They constituted the control group. 7–19 people were surveyed monthly. The inclusion criteria were children age from 10 to 15 years, the consent of the child, the parents signing a voluntary informed consent, bodyweight $\geq$95 percentile. The condition of children was assessed at the admission of children to treatment and the end of the rehabilitation course. Indexes measured in children were clinical and laboratory data: indexes of the immune system, biochemical and hormonal blood tests.

The control group included children of average physical development, blood pressure parameters not exceeding 90 percentile for given sex and age, without chronic diseases, in which there were no acute diseases within 3 months before the study.

All patients with obesity (200) were prescribed standard treatment. The complex consisted of a reduced-calorie diet, doing step aerobics on a daily basis, Sharko shower every other day (10 sessions), electro sleep every other day (10 sessions), sessions with a psychologist.

The diagnosis of obesity was established according to the accepted classification [3]. Centile tables of weight, height, waist circumference [9] were used to evaluate physical development. Indexes of waist circumference (WC) corresponding 90 or more percentile were evaluated as abdominal obesity. The body weight was evaluated using percentile tables of weight and bodyweight index (BWI) for a certain age and sex [10–12]. Blood pressure indexes were assessed by centile tables taking into account gender, age, height.

The total lipids content (TL), total cholesterol, triacylglycerides, cholesterol of high-density lipoproteins (TC, TG, HDL-C) in the blood serum of patients were determined using test systems produced by «Olvex Diagnostikum», Saint-Petersburg. The insulin content in blood serum was determined using an EIA kit for determination of insulin «Diagnostic System Laboratories». The HOMA-R index was calculated by the formula: HOMA-R = ENT × UIN/22,5, where ENT—fasting glucose, mol/l; UIN—the level of fasting insulin, mu/L. Cortisol was studied using sets of «SteroidIFA-cortisol» (SteroidEIA-cortisol). The study was performed on the EIA analyzer «Stat Fax 303 Plus» (USA). Veloergometry (VEM) was conducted on the cycle ergometer TUNTURI. According to the results of VEM indirect indexes of physical health—TFN (W), total work (units) and double product of systolic blood pressure on heart rate divided by 100 (double product, Rel. units) were determined. The psychoemotional status was assessed according to test methods (projective method Luscher color choices, the technique of Ch. D. Spielberger—Yu. L. Hanin to determine the level of personal and situational anxiety).

Assessment of immediate results of treatment was conducted according to a special adapted integrated modular system, health assessment, which is based on a unified system of standardization of the values of quantitative and qualitative indicators on a scale of Harrington [4–6] and the integral-modular assessment of health with the determination of an integral index of health (IPZ) [6]. When evaluating the effectiveness of treatment indexes that affect the patient's quality of life and indexes describing the development of metabolic disorders were used: complaints (level of appetite, fatigue, shortness of breath on exertion, headaches, discomfort associated with excess weight); objective measures (BWI, blood pressure, indicators of the functional state of the cardiovascular system (according to VEM); indicators of hormonal-metabolic status (fasting glucose, cholesterol level, HDL-C, TG, insulin); indicators of emotional state (level of stress, situational anxiety, emotional tension).

The upper and lower bounds of the norm were set for each index.

Baseline information about laboratory values can be formally represented in a matrix X_{mn}:

$$X_{mn} = \begin{pmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \dots & \dots & \dots & \dots \\ x_{m1} & x_{p2} & \dots & x_{mn} \end{pmatrix}$$

where n is the number of indexes; m—the number of children.

In addition, there are vectors characterizing the range of norm for each index, where vectors (x_{1H}, …, x_{nH}) and (x_{1B}, …, x_{nB})—lower and upper limits of normal values for healthy children.

This form of presentation enables the use of system modeling techniques in solving problems related to the selection of informative indexes and development on their basis of integrated indexes of health.

The method of description of nonlinear dynamic systems was used for the formation of the generalized performance evaluation of the condition of the investigated object and its changes. It is necessary to consider features of functioning of biological objects, namely that their characteristic stable equilibrium state, supported by internal and external energy resources and near which are made of cyclic metabolic processes. Depending on external conditions, equilibrium states themselves can change over time or maintain a constant value for a certain period of time. So it makes sense to consider properties of such systems and their characteristics in a small region defined by the admissible values of deviations from the equilibrium state.

Let's introduce the concept of dynamical systems, their state variables and determine the effects of the motion of such systems. For this we use the standard form of the mathematical description of the system and denote X(t) = {×1(t) × 2(t), …, xn(t)} as state variables; U(t) = {u1(t) u2(t), …, ur(t)} as their measures; W(t) = {w1(t) w2(t), …, wl(t)}—the external and internal energy resources. In the simplest case U(t) = C · X(t), where C is the identity matrix. In the general case, the system is nonlinear, characterized by the equilibrium values of the variables X0(t) W0(t), which can change over time, and their fluctuations in some acceptable limits. To introduce motion effect systems (which is what is of interest) we use the phase representation of condition coordinates and introduce the vector $\vec{y}_i(t) = \{x_i(t), \dot{x}_i(t)\}$.

The dynamic system is a system described by the differential equation in the form:

$$\dot{Y}(t) = F_Y\left(\vec{Y}(t), \vec{W}(t)\right), \tag{1}$$

where FY is a vector force field.

Using the state variables Eq. (1) can be rewritten in the form:

$$\ddot{X}(t) = F_X\left(X(t), \dot{X}(t), \vec{W}(t)\right), \tag{2}$$

Here F_X is a vector strength function that determines the motion of the system in a certain area.

The structure of Eq. (2) describes the behavior of the vector oscillator, in which sustained oscillations near equilibrium are supported by compensation for losses due to external and internal resources. As mentioned above, in the phase space such trajectories are limited on some hypersurface satisfying the condition

$$(X(t) - X_0)^T \cdot P \cdot (X(t) - X_0) + \left(\dot{X}(t) - \dot{X}_0\right)^T \cdot Q \cdot \left(\dot{X}(t) - \dot{X}_0\right) = V = \text{const.,} \quad (3)$$

Here P and Q are positive definite symmetric matrixes.

In the one-dimensional case, the hypersurface is expressed in the surface bounded by the ellipse.

The second term of the expression (3) determines the effects of the motion of the system and can serve as a generalized assessment of the functioning of the system on the time interval [t, t1]:

$$\gamma = \frac{\left(\dot{X}(t) - \dot{X}_0\right)^T \cdot Q \cdot \left(\dot{X}(t) - \dot{X}_0\right)}{V} = 1 - \frac{(X(t) - X_0)^T \cdot P \cdot (X(t) - X_0)}{V}$$

At the points X(t) = XA(t) velocity is zero $\dot{X}_\partial(t) = 0$ and $V_\partial = (X_\partial(t) - X_0)^T \cdot P \cdot (X_\partial(t) - X_0)$, then

$$\gamma = 1 - \frac{(X(t) - X_0)^T \cdot P \cdot (X(t) - X_0)}{(X_\partial(t) - X_0)^T \cdot P \cdot (X_\partial(t) - X_0)}$$

Let's introduce the index:

$$\kappa = \sqrt{\gamma - 1} = \sqrt{\frac{(X(t) - X_0)^T \cdot P \cdot (X(t) - X_0)}{(X_\partial(t) - X_0)^T \cdot P \cdot (X_\partial(t) - X_0)}}, \quad (4)$$

Here, changes in κ are in the range $0 \leq \kappa \leq 1$, and κ = 1 corresponds to health, and κ = 0 indicates the disease.

Before the application of the developed criteria in practice it is required to solve the following problems:

- to select informative indexes of the total number of registered, determine equilibrium values and tolerances;
- to choose the method of scaling of a source data to bring them to a single dimensionless measurement system for the subsequent merger of the integral index of health;
- to develop a method to evaluate the effectiveness of treatment based on an integrated index of health.

A Pareto chart was used to select informative indexes. It is simple enough to grasp by doctors and does not require sophisticated software solutions on the one hand, on the other hand, it provides speed and accuracy of calculations.

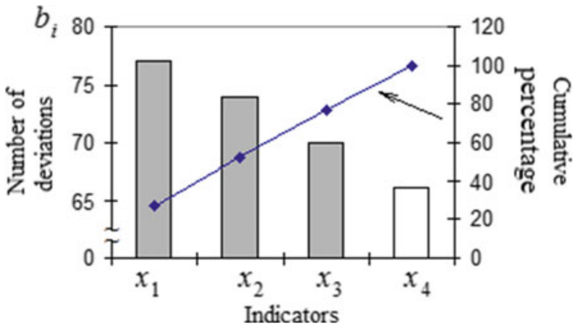

Fig. 1 Example of constructing a Pareto chart

A Pareto chart is a histogram in which each column reflects the relative contribution of every element in the studied problem, and all of them are ranked in descending order according to the degree of cumulative contribution from left to right.

According to the rule of constructing the Pareto chart, the source data is determined by the number of deviations of each index from the norm:

$$a_{ji} = \begin{cases} 0, & if\ x_{ji} \in (x_{iH}, x_{iB}); \\ 1, & if\ x_{ji} \notin (x_{iH}, x_{iB}); \end{cases}$$

$$b_i = \sum_{j=1}^{m} a_{ji} \tag{5}$$

where b_i—the number of deviations of the i-th index; x_{ji}—the value of i-th index for j-th patient; (x_{iH}, x_{iB})—the lower and the upper limit of the norm of the i-th index; $i = 1,\ldots,n$; n—number of indexes.

The received deviations are in descending order, and a bar chart is constructed, as shown in Fig. 1.

Afterward, the percentage of deviations of each index from the total number of deviations on the graph is calculated and a line of cumulative percentage is applied.

The determination of informative indexes is based on their cumulative percentage contribution to the process under study. In our case, the most informative indexes were taken as that contributing about 80%.

When calculating the integral index of health (IIH) it is necessary to combine variables of different scales. To make a valid comparison of values of different laboratory features scaling is usually used. The main issues of the scaling of the input information are, first, the choice of a suitable scale, secondly, the choice of the membership function.

In several papers [5–9] a scale of correspondences between the relations of preferences in the empirical and numerical systems in the form of standard markers (scale of preferences Table 1) is proposed to be used.

To do this, the so-called membership functions [5–7], based on which indexes are formed and defined health area preferred (desirable) state, denoted by the letter

Table 1 Empirical and numerical matching of the scale of preferences, CONV. units

The empirical system	Numerical system
Very well	1.00…0.80
Well	0.80…0.63
Satisfactory	0.63…0.37
Bad	0.37…0.20
Very bad	0.20…0.00

"d" from the English. desirable—desirable, are applied. These functions represent a natural way of transferring values into a single unitless numerical scale with fixed boundaries.

Specific ways of implementation of the membership function can be very diverse: expert functions, simple analytical functionы, the function of Harrington, etc.

In this chapter, we used the membership function of Harrington [13, 14] (Fig. 2), which in general terms, we can write down

$$\ln d(z_i) = -e^{-z_i}, \tag{6}$$

$$z_i = \frac{x_i - x_i}{x_{iB} - x_{iH}},$$

where d is the membership function; z_i is the coded value of the i-th indicator, which is a dimensionless value; xi—the value of i-th index in the original scale; x_{iH}, x_{iB}—lower and upper limits of the norm, respectively, for the i-th index in the original scale.

In this form, the function can be used for indexes limited from below. If the index has the limitation above, then it is necessary to use the "mirror" function by Harrington:

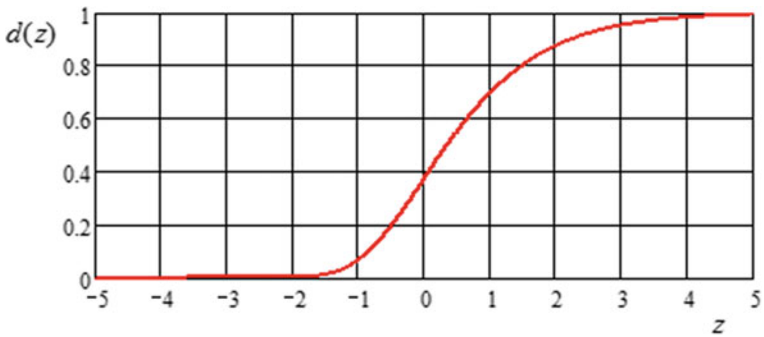

Fig. 2 The graph of the Harrington function for measures limited from below

$$\ln d(z) = -e^{z}, \tag{7}$$

If the index has bilateral constraints, it is necessary to take the proper value of the index or to calculate the average value for the interval constraints, if due importance is not set, and then use formula (6) for the left part of the interval constraints, and, respectively, formula (7) to the right.

After scaling and aligning the baseline to the interval [0–1], the formula (5) takes the form:

$$E = \sqrt{\frac{(d_1 - 1)^2 + (d_2 - 1)^2 + \ldots + (d_n - 1)^2}{n}} = \sqrt{\frac{1}{n}\sum\nolimits_{i=1}^{n} (d_i - 1)^2}, \tag{8}$$

where di is the value of initial indexes xi, that normalized to the interval [0–1]; n—number of indexes.

When calculating Euclidean distance, it is defined how far the patient under study is from the healthy man with ranging varieties equal to 1.

The integral index is easy to represent in percentage for medical workers. To do this it is necessary to subtract value E, calculated with the formula (8), for a certain patient from 1 to get the result in the form of the current value of the health level and not as the deviation from the norm:

$$\text{IIH} = (1 - E) \cdot 100\%, \tag{9}$$

To conclude the health condition of a patient, the integral of values of IIH from 0 to 100% one can divide so-called health levels according to the Harrington scale (Fig. 2).

The method of individual assessment of the state of human health based on clinical and functional parameters does not only provide the ability to make unbiased decisions but also allows their application in the evaluation of the effectiveness of sanatorium-resort treatment. It is necessary to determine the IIH before and after treatment. Besides, the introduction of the integral index allows predicting the effect of assigned treatment.

For experimental verification of the developed index together with Tomsk Research Institute of Balneology and physiotherapy the group of children and adolescents of both sexes aged from 7 to 15 years with thyroid disease and obesity as a concomitant pathology was created. The status of each child was assessed at admission to treatment and the end of the rehabilitation course based on a set of laboratory data. Also, the EEG recording remained for each child.

Children were divided into three groups for research purposes: the nature of obesity on hypothalamic (TH) and constitutional-exogenous (KEO), and the presence of thyropathology—endemic goiter (GOITER).

First of all, informative indicators of the total number of laboratory data in groups were selected with the Pareto method. As a result, the set of the analyzed laboratory indexes were reduced 2 times (from 34 to 17).

Differences in the composition of informative indexes for different groups of patients were differentiated, it will allow doctors to understand better their characteristics and to approach scheduling medical procedures on a case-by-case basis.

According to the formula (9), the integral index of health (Table 3) for all indexes and informative and uninformative indexes separately by groups was calculated. Obtained results confirm the accuracy of the selection of informative indexes and prove the possibility of their use for the assessment of children without losing significant information. In addition, the department of uninformative indexes allows to get rid of the noise and see the picture regarding the patient's condition better.

The ranking of the characteristics was carried out as follows: no abnormalities—1 point; above or below normal 25%–2 points, above or below the average correspond 26–50%–3 points; above or below the norm by more than 50%–4 points. IIH was represented in percentage, using the scale of Harrington (100–75%—the normal standard of health; 75–60%—moderate decline; 60–45%—a significant decline; <45%—a marked decline). The assessment of the treatment effect (Δ IIH = IIH after treatment. before treatment) was carried out with the use of a four-point system: Δ IIH more than 10.1%–3 points—a significant improvement; 5,1–10%–2 points—improvement, 0.1 to 5%–1 point—no change, 0% and less—decline.

3 The Result of the Study and Discussion

200 children with obesity were examined. The age of patients at the beginning of the disease was 6.5 ± 2.2 years. The disease duration was 4.5 ± 2.3 years (6 months to 10 years). Obese children had a family history of obesity—100 (50% children), thyroid diseases—10% (20 patients), diabetes mellitus type 2–11% (22 children), hypertension—23% (46 people).

Anthropometric indexes showed that all the children under observation had a hypersthenic constitution with highly developed subcutaneous fat. Excess body weight in children with obesity before treatment was 45.04 (22.10; 58.67) %, BMI was % to 28.91 (of 27.21; 30.17) kg/m^2. WC was consistent with the abdominal type of obesity in 42 (21%), which is a risk factor for metabolic disorders in these children.

For children with obesity, it was characteristic to have the tension of the psychoemotional sphere. Increase of levels of common stress (CS), situational anxiety (SA), and mental and emotional stress (MES during all months of the year, in comparison with healthy children ($p < 0.05$). A decline in physical performance and endurance was noted in children with obesity. A decline of tolerance to physical stress (according to VEM) was registered from December to July (average of 75.5 W), relative to healthy (92.1 (up 86.8; 97.4) W), $p < 0.05$.

Most of the researchers note mandatory for obesity changes in lipid metabolism [3, 7, 15]. A monthly study of lipid metabolism in healthy and obese children has revealed mixed trends in these indicators. Thus, the content of AL in blood serum from September to December and March was higher in healthy children ($p < 0.05$), and in January, February, April, and December—obese children, $p < 0.05$ (Table 1). The cholesterol level of healthy children was characterized by an increase from September through January relative to other months, $p < 0.05$. In patients with obesity cholesterol indexes exceeded the indexes of healthy people in February, spring (March, April, May), and summer months (June, July), $p < 0.05$. In September, minimum values of total cholesterol were recorded in children with obesity, in healthy people—maximum values, which is probably connected with different reactions at the beginning of the school year in healthy and obese children.

The increase of cholesterol level in children with obesity was observed in February, March, and June relatively to other months of the year, $p < 0.05$ (Table 1). Healthy children from September to October were noted with maximum content of HDL, compared to other months of the year. The decline of HDL in children with obesity, relatively healthy, was recorded in January, May, June, September, and October, $p < 0.05$. In February the lowest level of HDL-C was recorded in children with obesity of 1.09 (0,89; of 1.22) mmol/l and in October—the highest of 1.29 (1,06; of 1.65) mmol/l, $p < 0.05$. Maximum values of TG in the blood serum of healthy children were in the summer months (June–August), $p < 0.05$.

It is known that elevated levels of TG in childhood as predictors of the early development of cardiovascular disease in adults [3, 16]. In children with obesity the content of TG was higher than in the healthy group, $p < 0.05$ from February to May.

The content of insulin in the blood serum of obese children in almost all months of the year was significantly higher than in healthy children, but the maximum values were recorded in December as 20.6(11.5; 25.2) and March of 15.7(11.1V; 21.7), $p < 0{,}05$ in comparison with indicators of November 11,0(7,8; 14,3). The content of cortisol in blood serum in children with obesity in December, January, February, March, June, and July exceeded the same in the spring (April, May) and autumn (October and November) months, $p < 0.05$ (Tables 2 and 3).

Thus, in healthy children during the autumn–winter the intensification of lipid metabolism was noted, it can be considered as an adaptive reaction to cold time of year when the use of lipid energy in order to compensate for increased energy costs. We believe that the change in the lipid spectrum in children with obesity (relatively healthy) throughout the year can be regarded as the initial stage of the formation of lipid disorders [18, 19].

Table 2 The scale of correspondence of the integral index to the health level

IH, %	Health level
100…80	Normal
80…63	A slight decrease
63…37	A moderate decrease
37…20	A significant decrease
20…0	Marked decrease

Table 3 The integrated indicator of health (KEO)

Integral index health	All indexes		Informative		Uninformative	
	Before treatment, %	After treatment, %	Before treatment, %	After treatment, %	Before treatment, %	After treatment, %
Slight decline	45.53	64.23	47.15	66.66	98.38	99.19
Moderate decline	27.64	33.33	25.20	31.71	0.81	0.81
Dramatic decline	4.07	2.44	4.07	1.63	0.00	0.00
Prominent decline	22.76	0.00	23.58	0.00	0.81	0.00

On the basis of a monthly analysis of indicators of clinical and metabolic status in children with obesity, we hypothesized that the efficacy of standard integrated physio-balneotherapy in the time intervals of the year from December to April, from May to July, and from August to November will be different.

3 time periods were marked in the result of a search for the largest deviations of the studied indexes by months in children with obesity: from December to April, from May to July, and from August to November.

After treatment, the condition of obese children in all groups improved, frequency of complaints was reduced. All children tolerated treatment satisfactorily. After treatment, the standard complex had a decrease in body weight, WC, HC at all time periods of the year [1, 3, 10, 11]. The decline in physical performance (according to veloergometry) was observed from December to April and from May to July—before and after treatment, $p < 0.05$. The increase in exercise capacity was observed during treatment only from August to November, and 81.0 (78.3 per; 90.0) to 87.5 (85.0; 100.0) W, $p < 0.05$. The increase in «total work» was reported only in intervals from August to November and from May to July, $p < 0.05$.

The results of the study of mental and emotional status after application of complex treatment showed that in all time periods of the year the OS level of emotional stress (MES) reduced, $p < 0.05$. The increase in «total work» was reported only in intervals from August to November and from May to July, $p < 0.05$. However, the level of OS in children with obesity after treatment from August to November decreased by 12% and amounted to 6.0 (1.0; 9.0) scores. The level of ST in children treated from August to November, decreased by 24% and amounted to 37,0 (30.0; 42.0) scores, it did not differ from that of healthy children. The level of MES also decreased by 24%, $p < 0.05$. Thus, for children who were receiving treatment from August to November, improvement of emotional state was more pronounced, compared with patients who were treated in other time intervals.

After applying a standard set of treatments decrease of levels of TL and cholesterol was reported only from August to November. Change of TL made −0.10 (−1.10; to 0.20) mmol/l and TC −0,20 (−0.72; 0.43) mmol/L. From December to April, an increase of TC in the blood of obese children was reported after a complex treatment from 4.03 (3.25; 4.82) to 4.66 (3.77; 5.55) mmol/l, $p < 0.05$, and from May to July, the impact of the medical complex did not lead to the change of initially increased cholesterol level in the blood of obese children. The tendency for a decrease in TG in obese children after treatment was observed only from May to July with 0.78 (0.62; 0.97) to 0.72 (0.54; to 1.09) mmol/l, and in the period from December to April, the TG level after treatment was higher than the indexes of healthy children in the same time period of the year and was 0.94 (0.72 to; to 1.31) mmol/l, $p < 0.05$. Changes in HDL-C after treatment was not observed in any of the periods of the year (Table 1).

An important role of insulin resistance and leptin resistance is observed in the pathogenesis of obesity and related diabetes and metabolic syndrome [13, 20, 21]. Insulin levels in patients during the year did not differ between the groups and decreased after treatment ($p < 0.05$), but it was higher than the control values. Increased content of leptin treatment decreased in all groups ($p < 0.05$). Cortisol in all children did not go beyond the limit of control indexes both before and after treatment, which suggests that the assigned therapeutic complexes did not cause disorders of adaptive reactions of the organism [13, 22, 23].

4 Conclusion

Thus, high efficiency of standard treatment (including diet therapy, exercise therapy, Sharko shower, elektroantriebe, and psychotherapy) obese children is observed from August to November (an increase of integrated health indicator by 15.4%). In other months of the year, a correction of assigned complexes with regard to the obtained results is required.

The analysis of the contribution of individual indexes to change the value of the integral indexes of health was conducted. The result of the selection of informative indexes was that the number of analyzed laboratory data was cut in half, which significantly reduced the cost of examination of patients.

A generalized health index for the 3 groups of obese children was calculated, which allowed assessing the effectiveness of rehabilitation. When using a comprehensive assessment of the health status of children with obesity before and after treatment a pronounced positive effect only in the time interval from August to November was observed (an increase of IIH 15.4%). The effectiveness of the standard complex treatment of obese children from December to July was 1.6 and 1.7 times lower. From December to April, the impact of the standard complex was insufficient for the correction of disorders in the psychoemotional sphere (indexes of OS and ST), physical performance (indexes of exercise capacity and general work) and lipid metabolism (cholesterol and TG), which was reflected in a moderate increase of IIH (9.8%) after treatment. From May to July. IIH increased only by 9.2% after treatment due to the absence of pronounced dynamics of indexes of the psycho-emotional sphere (OS and ST) and physical performance.

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Society 5.0: Innovations in Socio-Economic Systems

Features of Protection of Intellectual Property Obtained Using Virtual and Augmented Reality Technologies

Oleg Slavin and Elena Grin

Abstract This chapter discusses the features of the application of modern technologies of virtual, augmented, and extended reality (XR) to obtain intellectual property. The chapter describes the capabilities of mass-produced products and prototypes for imitating various sensations: sight, hearing, touch, smell, taste. Describes the use of XR technologies for collecting and analyzing Big Data. Examples of such systems are CAD and training tools for specialists in complex systems. The types of tasks for training specialists using XR are considered. Lists the intellectual property that can be obtained using XR. Such objects include demonstrations, statistics on learning outcomes, models that include objects and how they interact, and others. The general and special methods of protecting intellectual rights are analyzed. Listed are the overriding preventive IP protections that can be obtained with XR. The important role of technical means of protecting intellectual rights, as well as virtual arbitration systems, is noted. The possibility of using blockchain technology for the sale and control of the intellectual property is indicated.

Keywords Virtual reality · Augmented reality · Extended reality · Virtual object · Objects of intellectual property · Terms of service · Data rights management

1 Introduction

Augmented and virtual reality technologies are digital technologies that affect the user through various devices.

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A typical representative of virtual reality is computer games. Virtual reality (VR) replaces the real world, affects the user, and considers his reactions. Augmented reality refers to technologies that supplement the real world with digital objects or replace objects in the real world. Representatives of augmented virtuality (AV) are computer programs for displaying cartographic information on the real world on a smartphone screen [1] or managing a group of wearable devices [2]. We will refer to XR (extended reality) as all types of augmented and virtual reality.

Currently, the large majority of augmented and virtual reality technologies are based on computer technology. Interaction with the user is realized using input components, which are responsible for controlling the user's reactions, and output components, which are responsible for influencing the user's sense organs.

We list the most famous XR devices.

Head-mounted displays (HMD) take the form of headsets and goggles to project two streams of video images into the user's eyes, protected from external light. Displays show stereoscopic video images that are offset relative to each other, which provide a realistic sense of a three-dimensional environment. HMD also reproduces multi-channel audio and assesses the user's position using sensors and accelerometers.

Headsets and user-independent goggles allow the user to analyze the space around them and add virtual objects to it. Most HMD have voice and motion recognition.

Other XR devices are virtual reality rooms, in which video images are displayed on walls, for example, based on 3D displays, which allow the user to create the illusion of a three-dimensional object by controlling the projection of a virtual object on the screen depending on the user's position. User orientation in virtual reality rooms or head-mounted displays can be digitized using treadmill sensors or foot platforms.

The listed virtual reality devices affect the user's vision and hearing by displaying video images and reproducing multichannel sound in headphones or acoustic surround sound systems.

Prototypes of devices for simulating gustatory sensations are under development [3]. There are studies of neuro interfaces in XR, which should allow getting rid of controllers or significantly reducing their number. The latter include electroencephalographic headsets (EEG headsets) for the extraction and analysis of electrical signals from the brain and transmission to a computer [4, 5].

The XR devices listed above provide a wide range of imitation sensations for use in both gaming and industrial processes.

However, the spread of XR technologies is hampered by many significant drawbacks that do not allow taking advantage of all the possibilities of augmented and virtual reality. The degree of full immersion in virtual reality (achieving immersiveness) is currently limited due to low display resolution and insufficient performance of mobile platforms or low mobility of powerful systems equipped with improved display devices. The main problems of augmented reality are associated with ergonomics, first of all, with a small viewing angle of screens of display devices. The listed problems of augmented and virtual reality devices can be gradually eliminated with further improvement.

It may be assumed that XR technologies can replace traditional user-computer interfaces. Bank of America Merrill Lynch in its study in 2016 indicated that, along with other technologies [6], XR will be an important element of the fourth industrial revolution. The turning point in the development of these technologies was expected in 2020–2021. However, today the market of XR technologies is not mass for many reasons, such as imperfections of the content and the implementation of devices for interaction with the user.

2 Background

The use of XR in various fields of activity allows not only to offer the user new tools but also to obtain with the help of these tools new knowledge and objects of interest to other users and organizations. With the help of virtual devices, it is possible to collect large amounts of data on the actions of users of a system designed for training, sports, or military purposes [7].

Let's consider several technologies that use augmented and virtual reality, in which the appearance of intellectual property objects is possible. This refers to objects created by users of a CAD system or by users of a training system simulator.

Modern CAD systems, being universal (Autodesk) or professional (Oceaneering, CATIA), are designed to create 3D models of various products, parts of products, and sets of products. Modeling is an essential CAD tool to reduce early design errors. The use of XR can significantly improve the ability of a CAD user to analyze the shape of an object by:

- navigation through the virtual presentation;
- modeling the conditions for using the product;
- improving ergonomics;
- improving user information;
- formation by the user of control signals and other characteristics.

The Digital Twin of the Organization, developing the concept of digital twins, is of particular relevance. A large amount of information about a complex object leads to the complexity of the perception of the description of the object, that is, to a reduction in the number of consumers. An adequate digital twin can reproduce the same parameters as its physical counterpart. This gives users the ability to simulate various operating conditions with the digital twin, without the risk of causing damage to the real object.

The Digital Twin of the Organization is an interactive digital twin built on 3D, VR or AR, AI and IoT, and BigData. The virtual twin allows using virtual reality devices not only to detail the perception of an object but also to implement various scripts of behavior with control signals.

The virtual twin exists on several levels:

- model of a part of an object;

– a complete model that combines all models of parts of an object.

The interaction of several technologies allows you to accurately repeat the process of a system or enterprise and to solve the following tasks:

– optimization of system functioning before commissioning;
– training of system personnel,
– monitoring of the system after launch.

An example of a software package operating in the geometric modeling environment Autodesk 3dsMax is described in [8]. The software package includes a module for outputting virtual models for printing on a 3D printer to check the adequacy of the designed equipment and modules for augmented and virtual reality (XR). These modules allow you to study the complex cause-and-effect relationships of industrial production facilities. The software package for creating a virtual twin of an industrial enterprise allows you to obtain design solutions based on the raw data (drawings, specifications, photographs, video materials) in the following form:

– the virtual three-dimensional geometric model with expansion,
– virtual video tours with expansion,
– applications for launching a virtual reality immersion module for workstations or mobile devices,
– file to be sent for 3D printing.

One of the most important capabilities of virtual twins of industrial enterprises is their use in the training of specialists. The most important tasks of training using virtual twins of training simulators [9–13] are:

– formation of target indicators of production and resource constraints;
– decomposition of the product life cycle into key production stages;
– identifying leading experts for each stage of the product life cycle.

One of the tools for training managerial production personnel to study modern industrial equipment, resource-saving control of technological processes based on virtual reality is the use of computer simulators [14, 15]. Modern directions in the development of intelligent computer simulators [16] are:

– development of cyber-physical systems and their introduction into the factory;
– application of augmented and virtual reality;
– use of intelligent human–machine interfaces.

The inclusion in the scientific and educational complex of computer systems for training specialists using XR allows solving the following tasks:

– readjustment of the factory for a new type of product;
– simulation of complex physical and chemical processes of obtaining industrial products;
– training in methods of accident-free maintenance of technological processes.

The result of the training of specialists in the formation of technological regulations for production. The work [17] indicates that the use of VR for training increases the accuracy of work and the speed of task completion by 46% and 29%, respectively. Technological regulations, visualized in the form of a detailed technological map of production, consider the requirements of the product sales market, the requirements of environmental safety, as well as the economic efficiency of each stage of the life cycle and production as a whole [18, 19].

3 Intellectual Property Obtained Using Augmented and Virtual Reality Technologies

A demonstration is a sequence of shots V(t), where t is a discrete-time, and $V = \{V1, V2, \ldots\}$ is a set of representations of one shot. Each of the shot representations is focused on influencing the viewer using various devices, for example:

- display devices on a flat screen, HMD, or virtual room screens;
- multichannel audio devices;
- devices for the synthesis of smells;
- tactile devices [20];
- devices for creating air streams [21];
- devices for simulating a water environment;
- devices for simulating gustatory sensations;
- temperature control devices [21].

Synchronizing user experiences is designed to enhance the viewing experience. The user should be able to customize the parameters of the V(t) shot representations, resulting in a parameterized demo V*(t) that differs from the standard original demonstration.

An interactive demonstration: $F(V) = \{V(t), e(t), u(t))\}$, where e(t) is the control of the influence on the user, u(t) is the control of the user. The e(t) control can be coordinated by various sensors of the state of the user, included in the XR technologies, and designed to assess the emotional impact on the viewer. The influence u(t) allows you to choose alternative demonstration options.

For a rather complex demonstration, several models $M(F) = \{<e^*(t), V^*(t)>\}$ can be obtained, far from the planned impact on the user and, accordingly, with different perception options.

Such models can be saved by the user on his technical means and transferred to the training database system. By analyzing the control actions e(t), models can be obtained that are focused on certain groups of users and are optimal for training users of these groups.

The generated models may be of interest to other users and are objects of intellectual property. The owner of the models is the owner of the training system, which includes simulators. The objects of intellectual property can be:

- images in various representations (flat or three-dimensional figures in a fixed form or video recording, audio recordings, smells, tactile and temperature signals, etc.);
- models that include objects and how they interact;
- presentations;
- statistics on learning;
- big datasets of data for testing;
- big datasets for training AI;
- technological regulations;
- testing procedure;
- user training methodology.

In CAD systems, in the process of functioning and improved interaction with multiple users, the parameters of devices, control models for product analysis are refined. As a result of specifying the parameters, it is possible that new models appear and can be considered as the results of intellectual activity. These results can relate to traditional types of intellectual property such as a system, device, substance, computer program, etc. However, the obtained results are complex objects whose descriptions M(O, t) consist of large data arrays and require other protection measures.

Some of the listed objects are objects of intellectual property.

For example, is a test procedure generated from a simulation of an unmanned vehicle suitable for testing a real prototype. Another example is parameterized mathematical models of a virtual industrial plant. These models can be exported from the training system to the monitoring systems of the operating enterprise. The use of one model in several systems increases its value and allows us to consider it as an object of intellectual property.

4 Protection Features of Intellectual Property Obtained Using Augmented and Virtual Reality Technologies

Due to the complexity of XR technologies, the protection of rights to the obtained results of intellectual activity must rely on several protection methods. Separate general and special methods of protection.

The general methods of protecting intellectual property rights include the following measures:

- recognition of rights;
- restoration of the situation that existed before the violation of the law;
- compensation for losses;
- self-defense rights.

Such measures are provided for, for example, by article 12 of the Civil Code of the Russian Federation. The choice of the protection method is not regulated. At the same time, general protection measures can be applied only in the absence of contradictions with the nature of intellectual rights.

Special methods of protecting intellectual property rights include the following measures:

- recovery of compensation in case of violation of the exclusive right to various results of intellectual activity and means of individualization,
- seizure and destruction of counterfeit material carriers,
- withdrawal from circulation and destruction at the expense of the violator of tools, equipment, or other means, mainly used or intended to violate exclusive rights,
- publication of a court decision on the committed violation with an indication of the actual rights holder.

Such measures are provided for, for example, in Articles 1250, 1252, 1253, 1474, 1515 of the Civil Code of the Russian Federation.

Many XR technologies are based on interactive demonstrations similar to gaming computer programs. Therefore, for most objects of intellectual rights in the field of the technologies under consideration, preventive protection measures are of primary importance. These measures include:

- use of contractual mechanisms,
- technical means of protecting intellectual property rights,
- other non-traditional ways to prevent infringement of intellectual property rights.

Let's consider each of these measures in more detail.

An important component of an overall XR intellectual property protection strategy is the effective use of contractual mechanisms in addition to other forms of intellectual property protection. These means include terms of service, as well as license agreements for use and terms of use [9, 22, 23].

Terms of Service are specially developed rules for using a service provided on the Internet via software or Internet service. Data Licenses and Terms of Use are contractual instruments designed to protect against misuse and misappropriation of data.

The considered contractual mechanisms are most effective for software (in particular, mobile applications) in the AR field. At the same time, the literature notes that the use of the terms of service in games that implement VR technologies is also a very effective measure. The terms of use provide VR developers with the ability to actively avoid legal action by users who are trying to defend intellectual property rights in virtual worlds.

It is noteworthy that the XR content developers may be directly responsible for the illegal use of intellectual property rights, including if they allow users of XR platforms to create and store content in their databases. In this regard, contractual protections are of paramount importance as they allow XR platform developers to address these issues by informing content producers that they must acquire exclusive rights or enter into a licensing agreement for intellectual property objects used in their virtual worlds [24].

For the first time, technical means as a separate way of protecting copyright and associated intellectual property rights were named in the civil legislation of the Russian Federation in 2014. According to paragraph 1 of Article 1299 of the Civil Code of the Russian Federation, technical means of copyright protection include any technologies, technical devices, or their components that control access to work, prevent or restrict the implementation of actions that are not permitted by the author or other rightsholder in relation of the work. The same provisions apply to the protection of associated intellectual property rights.

Examples of technical means of protecting copyright and associated intellectual property rights are the following measures:

– increasing overhead when copying;
– controlling the distribution of copies (for example, the six geographical areas of DVDs);
– protecting against unauthorized access.

For XR technologies, the most effective technical means of protecting intellectual property rights are:

– Data Rights Management;
– watermarks;
– copyright traps—deliberate errors or other actions that facilitate the possibility of proving the fact of copying the result of intellectual activity;
– technical tools for restricting access—the use of provisions of civil law prohibiting bypassing technical measures to prevent unauthorized access to copyrighted works (subparagraph 1, paragraph 2 of Article 1299 of the Civil Code of the Russian Federation).

The experience of the World Intellectual Property Organization (WIPO) in terms of the protection of the results of intellectual activity created in virtual reality is very interesting. In May 2020, the organization presented a new platform for the registration of intellectual rights—WIPO PROOF. According to the developers, this system allows protecting authors and the results of their creative work from idea to development and commercialization.

As part of this service, there is created a token, which is defined as a digital "fingerprint" of a file or information with a date and time stamp, which can be used as evidence in any legal dispute. You can buy such tokens either individually or in a bundle with a validity period of 2 years. To use the registration system, you need to go through user identification. The system is distinguished by confidentiality, independent verification, and the absence of reverse engineering.

Thus, due to the one-way hashing mechanism, it is ensured that it is impossible to reproduce the original digital file from the hash.

The application of the new WIPO PROOF accounting system is proposed to provide evidence of the existence of trade secrets and other undisclosed or shared assets; to provide evidence of the existence of creative works and designs, to facilitate licensing and transfer of rights. The developers also note that the system will be in demand for managing digital assets [25].

In addition to the specified WIPO system, other services have been developed and used to protect intellectual rights. For example, in the Russian Federation in 2017, the IPChain platform based on blockchain technology was created to sell and control the use of intellectual property. On the blockchain platform [26], the work license is transferred to the user in the form of an electronic key.

Foreign literature also received extensive coverage of the use of virtual arbitration systems [27] and virtual educational programs aimed at the preventive protection of intellectual property in the virtual space [12].

Virtual arbitration systems are understood as mechanisms for resolving disputes on the Internet. Such measures avoid litigation in the real world.

The advantages of this mechanism are:

– possibility of including conditions on such dispute resolution in contractual agreements;
– guaranteed resolution of the dispute by the end of the process (as opposed to negotiations and mediation);
– the presence of a procedure. In a dispute governed by arbitration mechanisms, an external arbitrator controls the process and decides on its result. Thus, arbitration can speed up the dispute resolution process.
– in-game arbitration reduces the costs that traditionally accompany court decisions.

5 Conclusion

At present, questions are being used on the application of traditional, existing domestic law, methods of protecting objects, created by technologies of existing and augmented reality. To protect intellectual property objects obtained using augmented reality technologies, one can use the existing mechanisms for protecting intellectual property objects in the Russian Federation, as well as world experience in this area.

The work highlights the following measures for the legal protection of the objects under consideration:

– use of contractual mechanisms;
– technical means of protecting intellectual rights;
– other non-traditional ways to prevent violations of intellectual property rights.

At the same time, we note that at present the traditional institutions for the protection of rights to the results of creative work are also applicable to the results used in modern and additional reality. The mechanisms of protection of rights provided for by copyright and patent law, as well as norms for the protection of means of individualization, are applied.

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Analysis of Russian Regions Innovative Competitiveness Dynamics Using Fuzzy Methods

Galina Chernyshova, Ekaterina Piunova, and Irina Veshneva

Abstract The problem of maintaining and improving regional competitiveness is related to the general concept of socio-economic development within the framework of the concept of Society 5.0. The purpose of this research is to apply digital technologies to implement new approaches to assessing and predicting regional development. Decision-making methods under a variety of possibly contradictory criteria are an effective tool for solving complex socio-economic problems, for providing objective and effective solutions, including in conditions of incomplete information, the uncertainty of macroeconomic conditions. The modified Fuzzy ELECTRE II method which allows applying different distance metrics in the algorithm was used for an integrated assessment of the competitiveness of regions. Approbation of the proposed approach is carried out on the example of an assessment of various aspects of regional competitiveness associated with the innovative development of regions. To assess the dynamics, innovative competitiveness ratings of 80 Russian regions for 2014 and 2019 were constructed. A comparative analysis of the obtained estimates allows us to identify regions that have the potential to develop competitiveness.

Keywords Digital model · Society 5.0 · Regional competitiveness assessment · Multi-criteria decision-making methods · Fuzzy ELECTRE · Ranking · Fuzzy methods · Decision-making systems

1 Introduction

As part of the modern approaches to assessing regional competitiveness, there are no generally accepted methods, and it leads to the use of different rating models to solve the problems of strategic planning and management. Mostly these ratings are

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integral indicators, taking into account various sets of competitiveness indicators. However, the use of integral indicators has significant limitations associated with the data availability, the presence of non-linear relationships between indicators, a certain degree of subjectivity in assessing the weight coefficients for individual indicators [1].

Predictive analytics of the regional competitiveness dynamics and the assessment of the corresponding risks are based on a limited statistical data set. At the same time, some of the significant quantitative and qualitative factors may remain outside the scope of official regional statistics, or the available data are not sufficiently representative.

The purpose of this study is to use multiple-criteria decision-making (MCDM) methods for an integrated assessment of individual factors of regional competitiveness. The main tasks are the development of a methodology for using MCDM methods based on fuzzy approaches to form a rating of the Russian region's competitiveness, application of the proposed approach for the competitiveness innovative factors estimation for different periods, modeling the dynamics of regions competitiveness development for further assessment and forecasting of competitiveness risks.

The fuzzy models make it possible to specify the intervals of preferred parameter values, without requiring quantitative information about the implementation of specific values within the specified interval. This avoids the use of averages. In the case of limited availability of quantitative information about the object of the quality of the initial information, a small volume of statistical samples, the approach based on fuzzy logic seems to be relevant.

The use of fuzzy estimates allows us to specify the intervals of preferred parameter values, without requiring quantitative information about the implementation of specific values within the specified interval. This avoids the use of averages. In the case of limited availability of quantitative information about the object or a small volume of statistical samplings, fuzzy modeling seems relevant.

2 Fuzzy Multiple-Criteria Decision-Making Methods

Multiple-criteria decision-making methods require that the selection is made among alternatives described by their attributes. It is assumed that tasks related to MCDM have a pre-determined finite number of alternatives, and their solution involves sorting or ranking. Multiple-criteria decision-making methods provide aggregation of criteria for selecting or ranking alternatives in the decision-making process. MCDM studies involve aggregation operators for multiple criteria and the application of different distance metrics in alternatives' evaluation.

Decision-making is often associated with inaccuracy and incompleteness of the data. One of the most relevant ways to solve this problem is the use of the concept the fuzzy sets [2]. The common approach to the classification of numerous MCDM methods is presented in Fig. 1. For a significant number of widely used methods

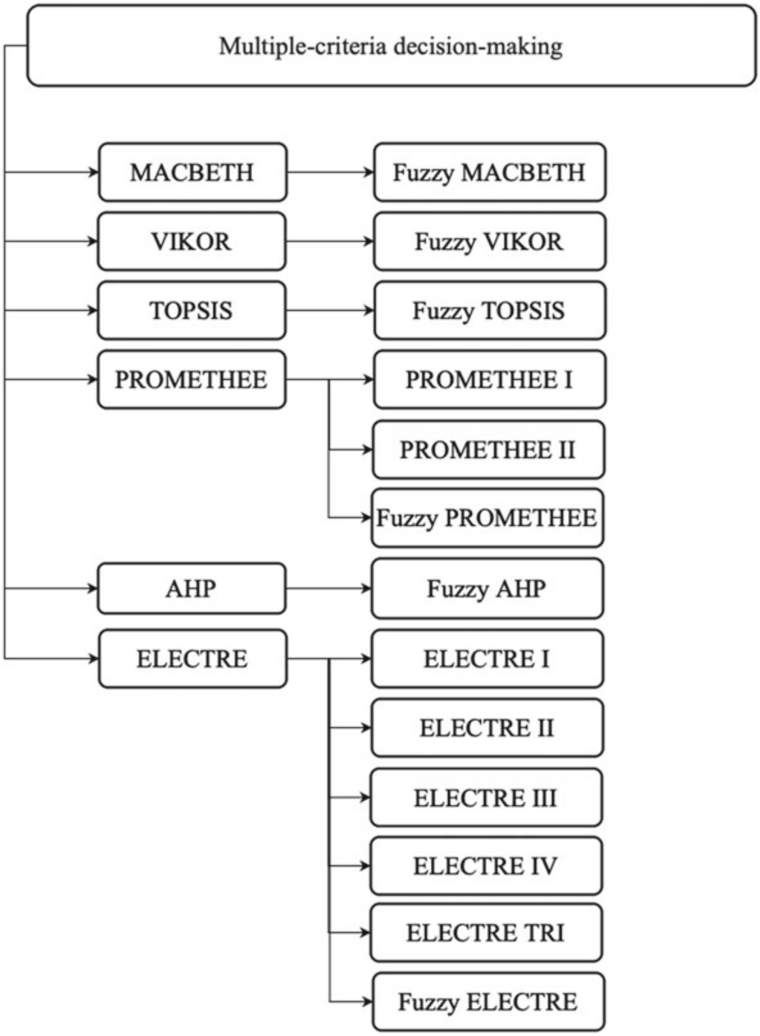

Fig. 1 Modifications of multiple-criteria decision-making methods using fuzzy approaches

(AHP, MACBETH, VICOR, TOPSIS PROMETHEE, ELECTRE), modifications using fuzzy sets have been developed. Methods based on interval and intuitionistic fuzzy sets have also been proposed for processing fuzzy information.

These modifications of the MCDM methods can be used in various applications (Table 1), while a quantitative assessment of alternatives is not required. Fuzzy methods are used to describe ambiguity when solution evaluating. An expert in the alternatives evaluating process can give linguistic assessments according to specified criteria by the selected scale.

Table 1 Application of a fuzzy approach in multiple-criteria decision-making methods

MCDM methods	Method modifications using a fuzzy approach	Applications areas	Источник
Fuzzy AHP	It allows you to eliminate the imbalance in the scale of judgments, the uncertainty, and subjectivity of the judgments of experts, to increase the accuracy of ranking	Assessment of financial performance of companies; evaluating student projects in education; software systems implementations	[3–5]
Fuzzy MACBETH	It uses qualitative judgments about the difference in attractiveness between the two alternatives to quantify the alternatives for each criterion and weight the criteria	Choice of waste disposal option	[6]
Fuzzy VIKOR	It maximizes group utility and minimizes individual losses, taking into account the preferences of the decision-maker	Manufacturing of customized high-quality products in batches of various sizes (agile manufacturing)	[7, 8]
Fuzzy TOPSIS	It allows to linearly order objects described using linguistic variables, the values of which are fuzzy numbers	Renewable energy assessment; green supplier selection problem	[9, 10]
Fuzzy PROMETHEE	It allows you to evaluate and select an alternative from a set, which is based on criteria that reflect the pros and cons of alternatives	Evaluation of the effectiveness of the programs of the Organization for Economic Cooperation and Development; Approach for Ranking Contaminated Sites Based on the Risk Assessment Paradigm	[11, 12]
Fuzzy ELECTRE	It implements a non-utility theory approach to the pairwise comparison of alternatives. The advantage of ELECTRE is that the further application of MMPR is carried out for a reduced set of alternatives	Supplier selection Selection of academic staff Comparison of infrastructure facilities Tourism destination competitiveness	[13–16]

ELECTRE (ELimination and Choice Translating REality) method and its modifications is a widespread method for solving applied problems. They are not based on the classical utility theory, and they apply relative assessments of alternatives. Binary dominance relations are built on alternatives set. The ELECTRE II method uses outranking consistency and inconsistency relations, and there are several levels of outranking relations. This method ranks the alternatives based on the threshold levels of consistency and inconsistency. ELECTRE II was further developed for processing ambiguous, indefinite, linguistic information [17–19]. Fuzzy ELECTRE II can use both qualitative and quantitative evaluations of criteria, to analyze the potential effects caused by the mismatch in the evaluation.

The standard Fuzzy ELECTRE II algorithm ranks the proposed alternatives using a single metric, such as Euclidean distance or Hamming distance. The choice of metric is an important aspect when comparing alternatives, while there are no generally accepted methods for choosing this parameter. The proposed algorithm uses the following metrics for ranking: Euclidean, Hamming, Hausdorff, Tanimoto—Jaccard, Zhuravlev, Manhattan, and Bray—Curtis. The final rating is based on the results obtained for individual metrics.

3 Methodology of the Regional Competitiveness Assessing by Modified Fuzzy ELECTRE II Algorithm

In the absence of a generally agreed methodology for assessing the competitiveness of Russian regions, an extended system of factors was proposed [1]. For a system-oriented analysis of regional competitiveness, the categories of transactional and transformational indicators are highlighted. The hierarchical system of indicators presents technical, social, natural resource, institutional, informational, innovative indicators [20]. Approbation of the proposed approach to assessing regional competitiveness is carried out for innovative indicators of competitiveness for the Russian region: x_1 is the internal R&D expenditure; x_2 is R&D personnel with the academic degree; x_3 is the innovative activity of organizations; x_4 is the volume of innovation goods.

The methodology for the integral assessment of competitiveness innovative factors includes the calculation of the integral indicator for different periods, ranking of regions, analysis of regional competitiveness dynamics in the context of innovative development. The calculation of the total indicator for ranking regions with the modified Fuzzy ELECTRE II algorithm can be represented as the following stages.

Step 1. Decision matrix construction.

Selection alternatives and criteria.

The criteria set is denoted by $X = \{x_1, x_2, \ldots, x_n\}$. Decision matrix elements represent an estimation of i-th alternative A_i, $i = 1, 2, \ldots, m$, for to the j-th criteria x_j. Fuzzy set A_i for i-th alternative for set X given by $A_i = \{\langle x_j, X_{ij}\rangle | x_j \in X\}$, where $X_{ij} = (\mu_{ij}, \upsilon_{ij})$. X_{ij} indicates membership and non-membership degree of i-th alternative for the j-th criteria x_j; μ_{ij}, υ_{ij} are membership and non-membership degrees X_{ij}, $0 \le \mu_{ij} + \upsilon_{ij} \le 1$, $i = 1, 2, \ldots, m$ and $j = 1, 2, \ldots, n$. $\pi_{ij} = 1 - \mu_{ij} - \upsilon_{ij}$.

1.2. Setting the criteria weights.

The weight vector W for the set X is:

$$W = \left\langle \langle x_j, w_j \rangle \middle| x_j \in X \right\rangle, \tag{1}$$

where w_j is the weight of criteria x_j, $0 \le w_j \le 1$, $\sum_{j=1}^{n} w_j = 1$.

1.3 Setting Decision Matrix M

$$M = \begin{matrix} A_1 \\ \vdots \\ A_m \end{matrix} \begin{bmatrix} X_{11} & \cdots & X_{1n} \\ \vdots & \ddots & \vdots \\ X_{m1} & \ldots & X_{mn} \end{bmatrix} = \begin{bmatrix} \mu_{11}, \upsilon_{11} & \cdots & \mu_{1n}, \upsilon_{1n} \\ \vdots & \ddots & \vdots \\ \mu_{m1}, \upsilon_{m1} & \ldots & \mu_{mn}, \upsilon_{mn} \end{bmatrix}. \tag{2}$$

Step 2. Defining concordance and discordance sets to compare alternatives.

Strong concordance set for A_k and A_l is defined as follows:

$$C_{kl} = \left\langle j \middle| \mu_{kj} \ge \mu_{lj} \wedge v_{kj} < v_{lj} \right\rangle. \tag{3}$$

Weak concordance set is defined:

$$C'_{kl} = \left\langle j \middle| \mu_{kj} \ge \mu_{lj} \wedge v_{kj} < v_{lj} \right\rangle. \tag{4}$$

Strong discordance set is defined as follows:

$$D_{kl} = \langle j | \mu_{kj} < \mu_{lj} \wedge \upsilon_{kj} \ge \upsilon_{lj} \rangle. \tag{5}$$

Weak discordance is defined:

$$D'_{kl} = \langle j | \mu_{kj} < \mu_{lj} \wedge \upsilon_{kj} < \upsilon_{lj} \rangle. \tag{6}$$

Step 3. Calculating the concordance matrix G.

Concordance index g_{kl} for A_k and A_l is calculated as follows:

$$g_{kl} = w_C \times \sum_{j \in Ckl} w_j + w_{C'} \times \sum_{j \in C'kl} w_{j,} \tag{7}$$

where w_C and $w_{C'}$ are the weights of strong concordance and weak concordance sets respectively.

Concordance matrix G is constructed as follows:

$$G = \begin{bmatrix} - & g_{12} & \cdots & \cdots & g_{1m} \\ g_{21} & - & g_{23} & \cdots & g_{2m} \\ \ldots & \ldots & - & \ldots & \ldots \\ g_{(m-1)1} & \cdots & \cdots & - & g_{(m-1)m} \\ g_{m1} & g_{m2} & \cdots & g_{m(m-1)} & - \end{bmatrix} \tag{8}$$

The maximum value of g_{kl} is denoted by g^* which is the ideal positive value.

Step 4. Calculating the discordance matrix H.

The discordance index h_{kl} for A_k and A_l is calculated as follows:

$$h_{kl} = \frac{\max_{j \in D_{kl}} \left(w_D^* \times d\left(X_{kj}, X_{lj}\right)\right)}{\max_{j \in J} d\left(X_{kj}, X_{lj}\right)} \tag{9}$$

where $d\left(X_{kj}, X_{lj}\right)$ is the distance between fuzzy sets according to the selected distance function; w_D^* is w_D or $\overline{w}_D$ depending on the different types of discordance sets.

Discordance matrix H is constructed as follows:

$$H = \begin{bmatrix} - & h_{12} & \ldots & \ldots & h_{1m} \\ h_{21} & - & h_{23} & \ldots & h_{2m} \\ \ldots & \cdots & - & \ldots & \ldots \\ h_{(m-1)1} & \cdots & \ldots & - & h_{(m-1)m} \\ h_{m1} & h_{m2} & \cdots & h_{m(m-1)} & - \end{bmatrix} \tag{10}$$

The maximum value h_{lk} denoted by h^* is which is the ideal negative value.

Step 5. Calculating concordance dominance matrix K.

The concordance dominance matrix K is constructed as follows:

$$L = \begin{bmatrix} - & k_{12} & \ldots & \ldots & k_{1m} \\ k_{21} & - & k_{23} & \ldots & k_{2m} \\ \ldots & \ldots & - & \ldots & \ldots \\ k_{(m-1)1} & \ldots & \ldots & - & k_{(m-1)m} \\ k_{m1} & k_{m2} & \ldots & k_{m(m-1)} & - \end{bmatrix} \tag{11}$$

where

$$k_{kl} = g^* - g_{kl} \tag{12}$$

Step 6. Calculating discordance dominance matrix L.

The discordance dominance matrix L is constructed as follows:

$$L = \begin{bmatrix} - & l_{12} \; \dots\dots & & l_{1m} \\ l_{21} & - \; l_{23} \; \dots & & l_{2m} \\ \dots & \dots - \; \dots & & \dots \\ l_{(m-1)1} & \dots \; \dots - & & l_{(m-1)m} \\ l_{m1} & l_{m2} \; \dots \; l_{m(m-1)} & & - \end{bmatrix}. \tag{13}$$

where

$$l_{kl} = h^* - h_{kl} \tag{14}$$

Step 7. Calculating total aggregate dominance matrix R from the concordance and discordance matrices.

The total aggregate dominance matrix R is constructed as follows:

$$L = \begin{bmatrix} - & r_{12} \; \dots\dots & & r_{1m} \\ r_{21} & - \; r_{23} \; \dots & & r_{2m} \\ \dots & \dots - \; \dots & & \dots \\ r_{(m-1)1} & \dots \; \dots - & & r_{(m-1)m} \\ r_{m1} & r_{m2} \; \dots \; r_{m(m-1)} & & - \end{bmatrix}, \tag{15}$$

where

$$r_{kl} = \frac{l_{kl}}{k_{kl} + l_{kl}}, \tag{16}$$

the values k_{kl} and l_{kl} are defined in (12) and (14).

Step 8. Alternatives ranking.

r_{kl} defines the relative closeness to the ideal solution in the range from 0 to 1. A higher value of r_{kl} means that the alternative A_k is both closer to the positive ideal and further from the negative ideal value than the alternative A_l. Thus, A_k is a better alternative.

The value of $\overline{T}_k$ is calculated:

$$\overline{T}_k = \frac{1}{m-1} \sum_{l=1, l \neq k}^{m} r_{kl}, \; k = 1, 2, \dots m. \tag{17}$$

All alternatives are ranked according to $\overline{T}_k$. The best alternative would be A^*, which is defined as follows: $A^* = \max\{\overline{T}_k\}$.

Step 9. Applying different metrics.

Steps 4–8 are performed for various metrics (Euclidean, Hamming, Hausdorff, Tanimoto – Jaccard, Zhuravlev, Manhattan, and Bray – Curtis). As the final estimation

$\tilde{T}_k$ of the alternative, the arithmetic mean of the $\overline{T}_k$ values obtained for given distance metrics are used.

To implement the modified algorithm, it was used developed application on the Python platform and the PostgreSQL DBMS. It allows us to obtain an integrated assessment of the innovative competitiveness of Russian regions with the specified criteria. As a result, the regions are ranked according to the degree of their innovative competitiveness.

4 Assessment of Russian Regions in Accordance with Innovative Competitiveness

As a set of alternatives, $A = \{a_1, a_2, \ldots, a_{80}\}$, 80 regions of the Russian Federation were selected, for which data are presented on the specified set of indicators in open sources for 2014 and 2019 [21]. To assess the level of innovative competitiveness, discretization of the competitiveness indicators values was carried out.

Table 2 presents a set $X = \{x_1, x_2, x_3, x_4\}$ of indicators for evaluating the innovative competitiveness criteria and the corresponding weight coefficients. It should be noted that the analysis of the sensitivity of the model to a change in the weight coefficients that determine the significance of the criteria has led to almost identical ratings.

The linguistic values of the criteria for the 5-level scale and the corresponding degrees of membership and non-membership are shown in Table 3. These degrees can be considered as indicators of satisfaction and dissatisfaction that the decision-maker uses for alternatives comparing.

Table 2 Weight coefficients of the criteria

Criterion	Weight coefficient
Internal R&D expenditure (x_1)	0,05
R&D personnel with the academic degree (x_2)	0,15
Innovation activity of organizations (x_3)	0,35
Volume of innovation goods (x_4)	0,45

Table 3 Parameters of the modified algorithm for regions estimation

Fuzzy criterion values	The degree of membership	The degree of non-membership
High	0,05	0,4
Above average	0,1	0,3
Average	0,15	0,15
Below Average	0,3	0,1
Low	0,4	0,05

The result of the considered methodology application is a list of regions ranked on the basis of an integral indicator for two periods with an interval of 5 years. The regions occupying the first 40 positions in the received rating in 2019 are presented in Table 4.

The use of fuzzy estimates for alternatives allows us to take into account minor changes of the values of the individual indicators that exceed the effect of changes of other attributes in the process of an integrated assessment. As a result, it can identify the dynamics of regional competitiveness for 80 regions of Russia over a five-year period when individual indicators could change slightly.

Quantitative assessments of the final estimate provide an opportunity to determine the direction and degree of innovative competitiveness changes (Fig. 2).

42.5% of the region showed no changes in innovative competitiveness five years. A slight positive trend was revealed in 32.5% of regions, 16.3% of regions have a slight decrease in competitiveness. Some regions (Nizhny Novgorod Region, Republic of Mordovia, Perm region, Belgorod Region, Udmurt Republic, Oryol Region) have significantly increased their innovative competitiveness.

To assess the dynamics of the competitiveness of the regions of the Russian Federation, it is proposed to carry out an analysis based on the values of the final estimate for the last period (2019) and changes in the value of the estimate from 2014 to 2019 (Fig. 3). As examples of best practice, the diagram shows the regions for which a high level of the final indicator was obtained, and a significant positive dynamic of competitiveness was demonstrated (similar to the Pareto optimal assessment).

The resulting estimates and the dynamics of competitiveness revealed regions that demonstrate some growth in these areas provided that in Russia, innovation activity does not increase significantly. It seems important to further research the experience and practices of similar regions in order to further develop and apply.

5 Conclusions

A special feature of the task related to the quantitative assessment of regional competitiveness is the presence of various uncertainty factors associated not only with the lack or insufficiency of quantitative data but also with the uncertainty of the external environment and the requirements for effectively improving the region's competitiveness. It is necessary to confirm the applied approaches to modeling with the accuracy and completeness of the available input data. The use of numerical estimates, in this case, seems to be a significant simplification of the model. Applying fuzzy approaches allows us to obtain more realistic estimates for complex socio-economic systems such as regions.

The proposed rating methodology based on the modified Fuzzy ELECTRE II method provides an integrated assessment of the Russian region's competitiveness and determining the dynamics of changes. In the absence of standard methods for assessing the level of innovative competitiveness, the use of multi-criteria methods

Table 4 Regional innovative competitiveness assessment in accordance with data for 2014 and 2019

Region	Final estimate, 2014	Rating value, 2014	Final estimate, 2019	Rating value, 2019	Final estimate difference
Moscow	0,6785	1	0,6597	1	−0,0188
Saint-Petersburg	0,6286	2	0,6086	2	−0,0200
Moscow region	0,6286	3	0,6086	3	−0,0200
Nizhny Novgorod region	0,4749	45	0,6086	4	0,1337
Republic of Mordovia	0,4442	62	0,5646	5	0,1204
Republic of Tatarstan	0,5259	30	0,5646	6	0,0387
Rostov region	0,5204	20	0,5646	7	0,0442
Belgorod region	0,4181	71	0,5646	8	0,1465
Sverdlovsk region	0,4825	43	0,5646	9	0,0821
Perm region	0,4449	59	0,5646	10	0,1197
Tyumen region	0,4749	50	0,5646	11	0,0897
Samara region	0,5259	28	0,5646	12	0,0387
Tomsk region	0,5881	14	0,5626	13	−0,0255
Republic of Bashkortastan	0,5849	5	0,5577	14	−0,0272
Ulyanovsk region	0,5204	21	0,5577	15	0,0373
Voronezh region	0,4838	44	0,5548	16	0,0710
Chuvash Republic	0,5828	13	0,5127	17	−0,0701
Kirov region	0,4442	66	0,5059	18	0,0617
Chelyabinsk region	0,5069	33	0,5059	19	−0,0010
Tula region	0,4749	53	0,5059	20	0,0310
Penza region	0,4442	65	0,5059	21	0,0617
Krasnoyarsk territory	0,5072	41	0,5057	22	−0,0015
Altai territory	0,5320	22	0,5057	23	−0,0263
Udmurt Republic	0,3556	75	0,5050	24	0,1494
Magadan region	0,5881	15	0,5015	25	−0,0866
Tver region	0,4830	55	0,5005	26	0,0175

(continued)

Table 4 (continued)

Region	Final estimate, 2014	Rating value, 2014	Final estimate, 2019	Rating value, 2019	Final estimate difference
Novosibirsk region	0,5849	6	0,5005	27	−0,0844
Vologda region	0,5849	10	0,5005	28	−0,0844
Yaroslavl region	0,4168	73	0,5005	29	0,0837
Vladimir region	0,4168	72	0,5005	30	0,0837
Kamchatka region	0,4749	52	0,4887	31	0,0138
Lipetsk region	0,4749	54	0,4887	32	0,0138
Ryazan region	0,5173	36	0,4887	33	−0,0286
Kaluga region	0,4605	58	0,4887	34	0,0282
Republic of Mariy El	0,5849	12	0,4887	35	−0,0962
Murmansk region	0,5320	23	0,4844	36	−0,0476
Tambov region	0,5259	27	0,4844	37	−0,0415
Khabarovsk territory	0,5069	34	0,4844	38	−0,0225
Bryansk region	0,5173	37	0,4844	39	−0,0329
Oryol region	0,3364	79	0,4844	40	0,1480

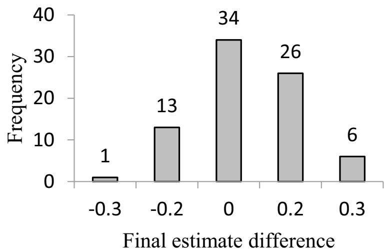

Fig. 2 Regions frequency distribution in accordance with the final estimate change of competitiveness

should be used to build a comprehensive system focused on identifying best practices. The identification of positive changes in the innovative development of regions detects perspective directions of improving competitiveness for other regions, and further reducing the risks of regional competitiveness.

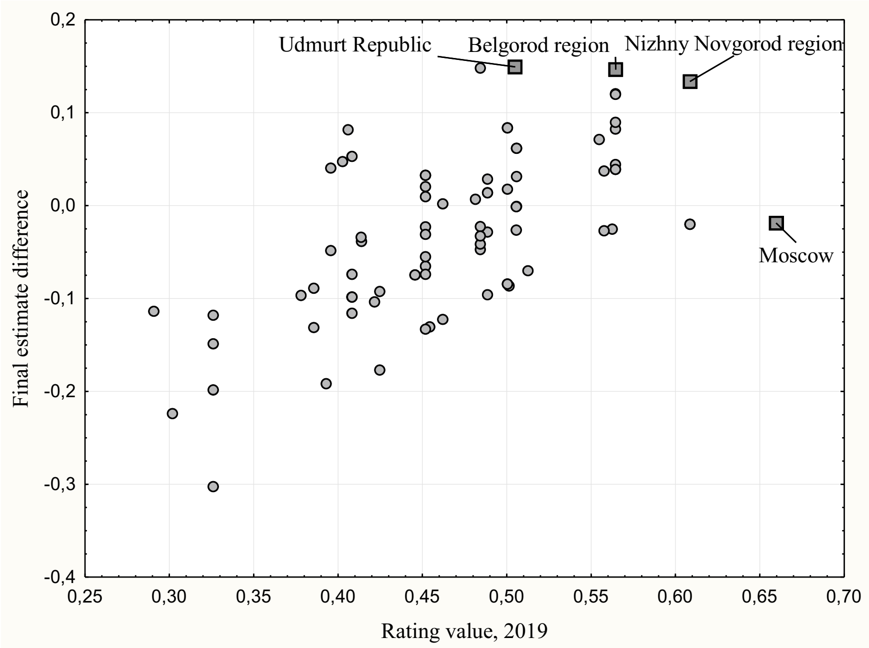

Fig. 3 Dynamics of changes in regional innovative competitiveness

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Construction of Digital Twins of Socio-Economic Systems Using Mathematical Models Based on Status Functions

Irina Veshneva and Alexander A. Bolshakov

Abstract The problem of the development of mathematical models for the construction of digital twins of socio-economic structures associated with certain specific features is shown. The use of complex mathematical models of digital twins of socio-economic systems based on the mathematical apparatus of status functions is proposed. In this regard, the formulation of the problem of developing new mathematical models for determining the state of socio-economic systems has been formulated. The classification of approaches to the digitalization of socio-economic systems is described. It is shown that the integration of digital twins into the classical control system is associated with the traditional implementation of the functions of observation, analysis, and control. Trends in the synthesis of digital twins for use in socio-economic structures are described, which are associated with an increase in the number of states, an increase in productivity, and more complex requirements for the structure and quality of the estimated parameter values. The concept of development and integration of new mathematical models using status functions is proposed. The architecture of an integrated platform of a cyber-physical system has been developed using mathematical modeling for the application of effective mathematical methods based on status functions. An example of the implementation of the stage of the proposed concept associated with the construction of a complex of problem-oriented programs is considered. Expressions for basic status functions are obtained on the basis of the linguistic description of the values of variables and data of the FIRA PRO system, and the corresponding graphs are also built.

Keywords Digital twins · Cyber-physical systems · Socio-economic structures · Mathematical models · Status functions

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1 Introduction

The development of Industry 4.0 [1] is associated with the industrial revolution characterized by the following features: new energy technologies are not used, new raw materials are massively used, a significant increase in the energy efficiency of production, the ability to predict the future, a significant acceleration of modernization and the emergence of an exponential increase in labor productivity. In the industrialized countries of Europe and North America, states are the sources of the actors of the ongoing changes. In Russia, a national project for increasing labor productivity has been proposed, which presents the goal of ensuring by 2024 the rate of increase in labor productivity in organizations belonging to the basic, non-resource sectors of at least 5% per year. By 2024, it is planned to increase labor productivity by more than 20%. This will allow the Russian Federation to move to the level of the world's leading economies. The modern fourth industrial revolution has features similar to the previous ones: the modernization of production technology depends on the improvement of the management system. At the same time, for more complex technologies it is required to increase the relative volume of automated control systems. Experts say that more than 40% of enterprises use digital technologies at a critical level, then an exponential growth of industry digitalization is expected [2, 3]. Such digitalization requires the massive implementation of cyber-physical systems capable of self-tuning and adapting to the new needs of manufacturers and consumers.

The structure of these changes includes the following distinctive features: Internet of Things (IoT for short) [4, 5]; digital twins (Digital Twin) [6]; 3-D printing [7–9]; cloud computing and big data [10–12]; cybersecurity [13, 14]; digital platforms [15].

The fourth industrial revolution has begun, its distinctive features are manifested quite clearly and extensively. At the same time, it can be argued with confidence that, as in previous revolutions, the one who is able to create, develop and use technologies of distinctive features earlier than others will gain an advantage over other enterprises and countries, and the gap will grow exponentially.

According to expert estimates, the benefits will be given to organizations that are actively working with innovations and have their own competencies in the aspect of digitalization.

One of the possible obstacles is the lack of innovative technologies and models. Fundamentally new technology for constructing and using mathematical models and automated control systems can be based on mathematical models using the mathematical apparatus of status functions [16].

Moreover, in this regard, the problem is the need to develop possible mathematical models of digital twins of socio-economic structures that differ from the known models in specific features.

Let us present a model for the formation of digital twins of socio-economic structures based on status functions developed and proposed in [17].

2 Statement of the Problem of Creating New Mathematical Models for Assessing the State of Socio-Economic Systems

The process of integrating digital twins (CDs) into the classical control system is actively developing in each of the following functions.

1. Observation function. There is a change in the technological order. Industry 4.0 deals with completely new phenomena that are digital in nature. Digital Twin in our case is a software analogue of the socio-economic system (SES).
2. Control function. synthesis and improvement of CD.

A brief description of the subject area of SES digitalization is given in Table 1.

The analysis performed in Table 1 shows that the development of models of the CSD of socio-economic structures finds application in the analysis of big data and predictive analytics for the formation of forecasts based on new mathematical models. At the same time, communication between socio-economic structures can be carried out using the CD. Then the communication in the system governing body—controlled socio-economic object can be reduced to the model of meta-communications: governing body—CD—managed socio-economic object, managed socio-economic object—CD—the governing body. The new data analysis model will create a virtual integrated environment for big data analysis and predictive analytics. In the new integrated complex, in the implementation of management actions using big data based on the central data center using problem-oriented software tools, the corresponding technological and technical platform is created by cyber-physical systems. For the synthesis of this organizational and technical platform, the technology of building a CD is of decisive importance.

3. Functions of analysis, management. These functions are required to be provided in the architecture of a functioning integrated platform of a cyber-physical system. When implementing these functions, significant difficulties arise: limited resources, possible lack of feedback in the subsystem: the governing body is a controlled socio-economic system.

A cyber-physical system includes a set of interacting components to achieve a single goal in the control process [17]. Mathematical models of such complex complexes generally correspond to the main provisions of synergetic [18] and are created on the basis of methods developed in physics, chemistry, and biology [19].

The difficulty of using mathematical models and methods is associated with the lack of measurement scales that are used in natural sciences (measurement of speed in m / s, mass in kg, etc.). To overcome it, it is advisable to use linguistic variables to describe, for example, psychophysiological indicators in ergatic systems based on the theory of fuzzy sets [20], as well as to interpret data obtained in the course of field experiments using the so-called status functions (SF).

The SF-based algorithm allows you to enter linguistic assessments and represent them with complex-valued functions, called status functions. Mathematical models

Table 1 Classification of approaches to the digitalization of SES

Method of digitalization	Characteristics of the digitalization method
Process Automation (RBA)	Implementation of robotization of operational activities, which allows to reduce the duration of these operations and increase efficiency and / or efficiency by up to 80% based on a decrease in the payroll, as well as reducing the risks of operational activities
Big Data and related methods of analysis and interpretation	Improving the performance of the company based on increasing the speed and volume of processed information. Using predictive analytics to build forecasting procedures when processing large amounts of data. At the same time, statistical methods for processing multidimensional data, analysis of historical data, and procedures for planning expected results are used
Reference and information retrieval and reference complexes (systems)	Implementation of the functions of forming the required information, obtaining the required competencies for the systematization and analysis of data
Chat robots	Software tools that run in applications. At the same time, they can imitate speech and text for organizing interaction to find the required data
Artificial Intelligence (AI)	Used to perform complex tasks by programs and optimize the use of human resources
Virtual and Augmented Reality	Technologies of projection or augmentation of reality by technical means to reduce the cost of the implemented processes
Internet of things (IoT)	A network of components that interact, for example, a set of sensors for collecting data, remote information exchange to improve the efficiency of solutions
Pattern recognition OCR/ICR	The technology is capable of replacing a person in the process of receiving, analyzing, and verifying documents; it is designed to digitize document flow, security systems, and customer service
Blockchain	Technologies make it possible to form various training situations in which the learning process is carried out in the form of a game

based on SF are devoid of many of the shortcomings of classical models of socio-economic processes, such as static nature and the impossibility of taking into account the intersection and mutual influence of the studied components of the processes.

The main trends in the synthesis of CSD of socio-economic systems (SES) are as follows:

1. an increase in the number of states that are evaluated, as well as the components of the data structure that are subject to analysis;

2. increasing the productivity and complexity of information platforms for the implementation of problem-oriented software tools;
3. the complication of requirements for the structure and quality of the estimated values of the SES parameters, the multicomponent nature of the nested structures of the estimates, the overlap and complexity of the processes that are implemented in socio-economic systems;
4. activation of subjects and processes of interaction in organizing management to increase the degree of its automation.

This raises the problem of creating mathematical models that allow increasing the number of controlled variables and parameters to automate the used decision support process (DSS). This initiates the use of modern technologies, techniques and corresponding mathematical methods [19, 20]. So, when developing new methods of managing the educational process, various models are actively used, fuzzy, boolean, etc.

Thus, the development of new methods for assessing the state of socio-economic systems, taking into account the complexity, subjectivity and multidimensionality is a very urgent problem. It is advisable to apply the proposed mathematical method in the construction of an intelligent monitoring system, as well as PM in the analysis of indicators of the functioning of the SES, such as, for example, individual enterprises or the structure of indicators of the activities of the regions of the Russian Federation to increase the effectiveness and efficiency of management according to the characteristics of the SES and the successful solution of problems caused by the goals of functioning. management systems for individual enterprises or regions.

3 The Concept of Development and Integration of New Mathematical Models

The concept of mathematical modelling based on effective mathematical methods and building a model that describes ergatic interactions in the form of corresponding communications of digital twins based on an integrated platform for various cyber-physical systems, it is advisable to display as a sequence of five stages (see Fig. 1).

Stage 1. Interpretation of data obtained as a result of field experiments. At this stage, an analysis of the data of the controlled variables of the SES is required. So, for example, the analysis of indicators of socio-economic activity of the regions of the Russian Federation and models was carried out in works [22, 23].

Stage 2. Mathematical modelling of socio-economic processes and objects. The best basis that is advisable to use for the synthesis of mathematical models of digital twins is SF. From their combination, it is possible to form the final mathematical models, which are proposed and presented in the article [14]. The new mathematical model allows building an integrated platform for cyber-physical systems. On this platform, it is advisable to implement training for the synthesis of hybrid ergatic systems.

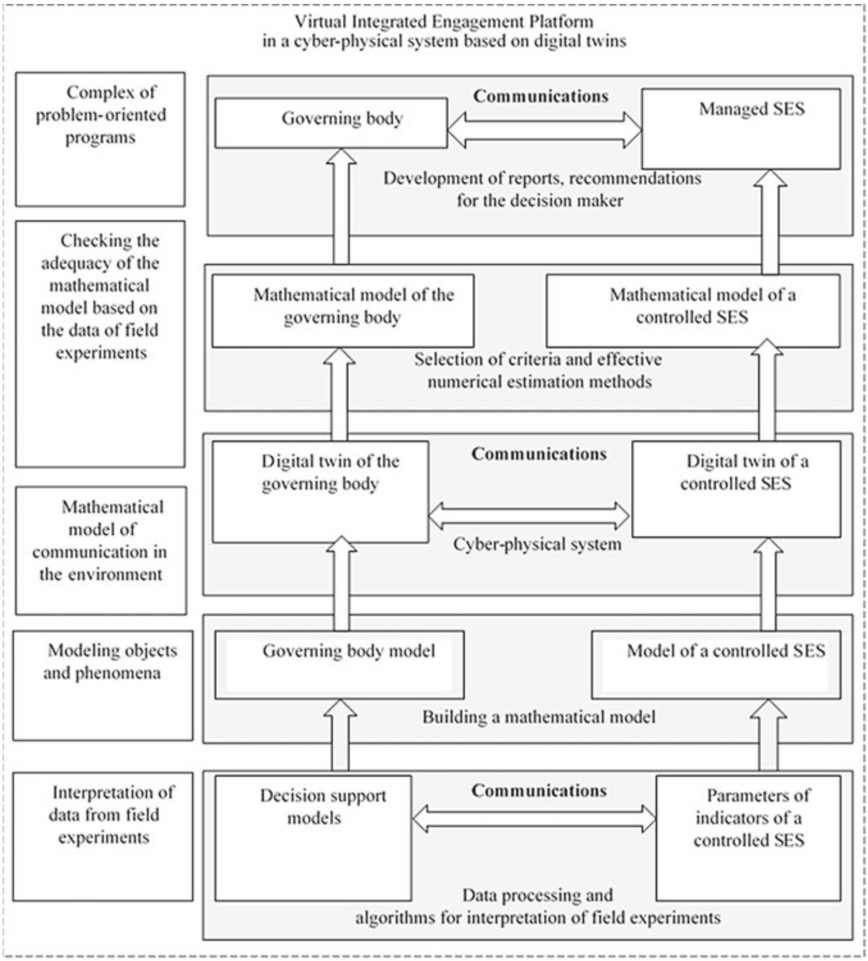


Fig. 1 Architecture of an integrated cyber-physical system platform using mathematical modelling to apply effective mathematical methods based on status functions

Stage 3. Mathematical model of communications in the environment. We will focus on meta-communication in a cyber-physical system. Moreover, the direct communication and interaction of the governing body—the managed socio-economic object are replaced by meta-communication of digital twins: the governing body—the central office—the managed socio-economic object, the managed socio-economic object—the central office—the governing body.

Stage 4. Checking the adequacy of the proposed mathematical models using data from field experiments. It is advisable to interpret the information obtained as a result of experiments by the SF method, as well as on the basis of the Kolmogorov-Chapman equations [25, 26] based on the data obtained in the FIRA PRO system.

Stage 5. The complex of problem-oriented software. Below is a description of the architecture for assessing the parameters for assessing the activities of SES on the example of assessing the competitiveness of the regions of the Russian Federation.

4 Example of Implementation of the Concept

Let us describe the 5th stage of building a complex of problem-oriented programs. First, based on the collection of data, a linguistic description of the assessment results is formed. To assess the state of the variables "Degree of depreciation of fixed assets", "The number of populations with incomes below the subsistence level", "The number of official unemployed", "Dilapidated and dilapidated housing", "Debt on taxes and fees", Table 2 with the corresponding linguistic description is used. For the generated assessment tables, SFs are put into correspondence, which are presented in Table 3.

Basic SF values consist of two parts: amplitude and phase. The amplitude parts are real and are shown in Table 4. They are the orthonormal basis of the system and represent a set of basis functions that can describe all possible states of the system. The phase part of the SF is complex and indicates the direction of the trend—or in which direction the shift of the mathematical value of the SF is expected.

As a result, the corresponding complex-valued status functions (SF) are formed.

Secondly, the formation of hierarchical interconnected structures is carried out. The result is a causal graph (see Fig. 2).

In the diagram shown in Fig. 2 structure of the following indicators: the cost of fixed assets (E29); depreciation rate of fixed assets (E30); density of railway tracks

Table 2 Linguistic description of variables for data from the FIRA PRO system

	Interpretation of parameter values based on FIRA PRO data		
Trend assessment	High values of the indicator, it has been growing for the last 3 years, more than 10% higher than the same indicator in neighboring regions	The maximum permissible threshold value, reached as a result of a decrease in the indicator	Low values of the indicator, it has been growing for the last 3 years, more than 10% lower than the same indicator in neighboring regions
	High values, changes over 3 years within the margin of error	Maximum permissible threshold value, changes within 3 years within the margin of error	Low values, changes over 3 years within the margin of error
	High values of the indicator, it has been growing for the last 3 years	The maximum permissible threshold value, reached as a result of an increase in the indicator	High values of the indicator, decreasing for the last 3 years

Table 3 Expressions of basic SFs for substitution in accordance with the table of linguistic description of variable values for data from the FIRA PRO system

	Mathematical expressions of estimates in accordance with the parameter interpretation table		
Evaluation of the trend yes	Low = 3.37619 (e-50. r+0.142-0.580252e-22.2222 r2 e-i2πr	Middle = 1.9394e-22.2222r2 e-i2πr	High = 1.37668 e-(14. -50.r)r +1.87105e(14. -50.r)r --5.02117e-22.2222r2 e-i2πr
	Low = 3.37619 (e-50. r+0.142-0.580252e-22.2222 r2	Middle = 1.9394 e-22.2222r2	High = 1.37668 e-(14. -50.r)r +1.87105e(14. -50.r)r --5.02117e-22.2222r2
	Low = 3.37619 (e-50. r+0.142-0.580252e-22.2222 r2 ei2πr	Middle = 1.9394 e-22.2222r2 ei2πr	High = 1.37668 e-(14. -50.r)r +1.87105e(14. -50.r)r --5.02117e-22.2222r2 ei2πr

(E31); road density (E32); per capita money income (E33); population with incomes below the subsistence level (E34); the number of officially unemployed people (E35); life expectancy (E36); population growth rate (E37); migration growth rate (E38); dilapidated and dilapidated housing (E39); the number of doctors per 10,000 population (E40); the number of reported crimes (E41); emissions of polluting products (E42); discharge into water bodies of polluted wastewater (E43) was obtained as a result of data collection and analysis [28, 29]. The rest of the indicators uniting leaf vertices into a causal graph were introduced as a result of logical operations presented in [16].

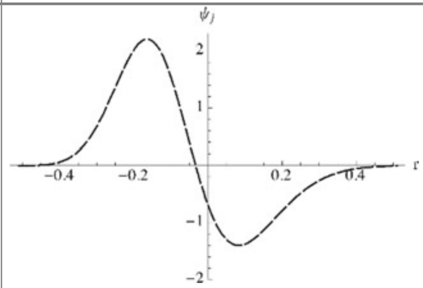
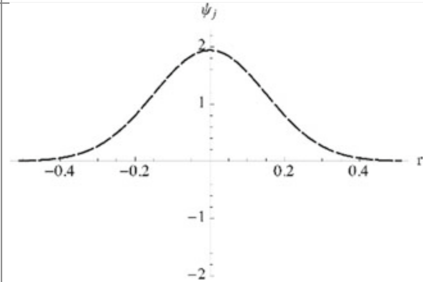
Third, a system of differential operators is formed for the structure of groups of higher indicators. As a result, the system of differential equations based on SF becomes an analogue of the described structure. The system is obtained similarly to Forrester's equations of world dynamics.

Note that recently, in general, interest in the use of modern mathematical models, digital technologies for mathematical modelling of socio-economic systems using the ideas of digital twins have increased significantly [29, 30].

5 Conclusion

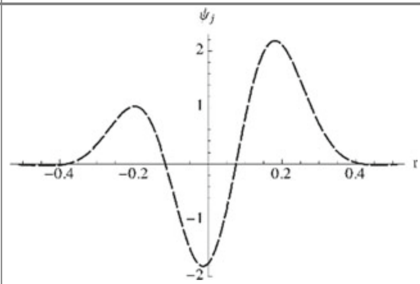
Thus, based on the estimates presented by the SF method, it is possible to construct dynamic models of digital twins for use in cyber-physical systems. Structures that can be built on the basis of status functions can be simply formed from models for evaluating indicators based on linguistic terms. Status functions are a "bridge" between a person's simple ideas about the world around him and phenomena to the

Table 4 Examples of linguistic estimates, mathematical expressions and the form of the amplitude part of the basic SF

Example of linguistic assessment	Status function	Graphics
High values of the indicator, it has been growing for the last 3 years, more than 10% higher than the same indicator in neighboring regions	Low = 3.37619 (e-50. r + 0.142–0.580252e-22.2222 r2	
High values, changes over 3 years within the margin of error	middle = 1.9394 e-22.2222r2	

(continued)

Table 4 (continued)

Example of linguistic assessment	Status function	Graphics
High values of the indicator, it has been growing for the last 3 years	high = 1.37668 e-(14. -50.r)r + 1.87105e(14. -50.r)r –5.02117e-22.2222r2	

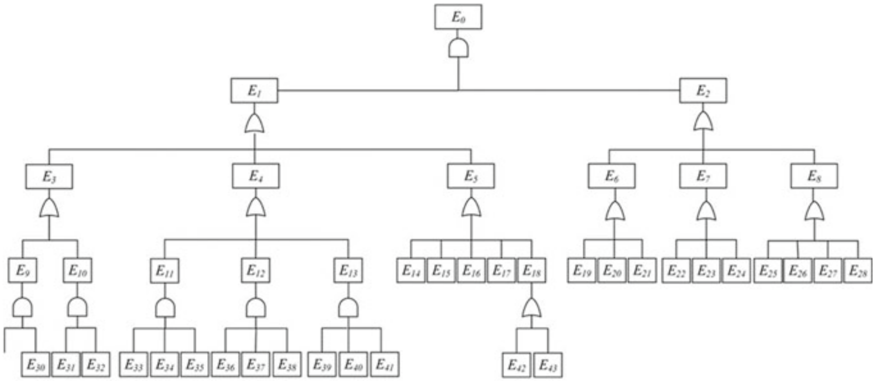


Fig. 2 A causal graph for assessing the risks of regional competitiveness

strict uncertainty of quantum mechanics. The advantage of the model is that it takes into account the complexity, high degree of uncertainty, and the intersection of socio-economic processes. Models allow building-level structures of possible states. The main advantage is the predictivity of the model and its suitability both for predictions and for describing meta-interactions in an integrated environment of cyber-physical systems.

The proposed generalized scheme of mathematical modeling based on the use of effective numerical methods and a complex of problem-oriented programs is advisable to use to assess communications in an integrated environment of cyber-physical systems based on status functions.

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Development of a Mathematical Model for Decision Support Systems in Social Structures Based on the Formation of Assessments of the Competitiveness of the Regions of the Russian Federation

Irina Veshneva and Alexander A. Bolshakov

Abstract The problem of constructing a mathematical model for assessing the competitiveness of the regions of the Russian Federation has been formulated and solved. For this, a structuring method based on hierarchical trees is proposed. Their leaves are statistical indicators of socio-economic activity according to official data. These indicators are combined using integral characteristics. An example of the analysis of networks of socio-economic indicators based on the construction of minimum sections of the Kolmogorov-Chapman equations for the "Innovation" indicator is given. To describe the leaf vertices of the indicator trees, it is proposed to use status functions that represent complex-valued functions. The proposed mathematical model represents a system of integrodifferential equations, including the status function for the integral indicator of the competitiveness of the region, functions for each of the integral indicators, polynomials that are obtained as a result of interpolation of statistical data, and management influences. The analysis of the obtained graphs of the normalized values of several static indicators, the assessment of trends is given. The possibility of using numerical methods of nonlinear dynamics based on status functions to take into account the cross-section and mutual influence of the parameters of the risks of competitiveness of the regions of the Russian Federation for use in decision support systems in cyber-physical systems is shown.

Keywords Kolmogorov-Chapman equations · Decision support system · The competitiveness of regions · Graph of causal relationships · Status functions · Cyber-physical systems

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1 Introduction

Ensuring an adequate level of competitiveness of the Russian economy is associated with significant structural changes of a technological and organizational nature, both at the international and regional levels [1–5]. In this regard, the formation of a modern mathematical model of the competitiveness of regions is in demand [6–8]. Note that mathematical modeling, well developed in physics, hydrodynamics, quantum mechanics, chemistry, biology, nanotechnology, medicine, and other sciences, allows one to synthesize processes, materials, and new material structures, which cannot be created and controlled without predictive mathematical models.

At the same time, modeling in socio-economic systems "lags" behind the natural sciences. Moreover, to understand the processes in society and manage them using artificial intelligence, appropriate mathematical models are needed. However, the required mathematical models are difficult to create and even more difficult to test. Consider, for example, a laser. For the components of its structure, many mathematical models can be assembled, folded like constructor cubes. Then write a program, test the dependence on parameters, getting, for example, millions of data on 100 by 100-point grid structures. Then you need to check them with the experiment, get the result and data sets for further research based on them.

However, if we consider the structure of the socio-economic system (SES) as a cyber-physical system (CPS), then it will be necessary to synthesize and collect thousands of indicators into the structure [9]. The next task is to collect the real values of these indicators. This process is laborious and time-consuming. Analysis of changes over time is an even more difficult task since the social network changes during data collection and the structure of SES economic indicators is also not invariant and changes over time. Therefore, the problem arises of creating such structures so that it is possible to create reproducible algorithms for the dynamics of these processes in time for use in the FSC of the studied socio-economic processes.

2 Statement of the Problem of Developing a Mathematical Model for Intelligent Decision Support Systems

The construction of a mathematical model for intelligent decision support systems seems to be an urgent task in the process of overcoming imbalances in the socio-economic development of Russian regions [6, 7].

Let us consider in more detail the direction of research from the point of view of developing methodological and analytical tools for assessing the dynamics of risks [10, 11] to the competitiveness of Russian regions using artificial intelligence and methods of cyber-physical systems.

The aim is to assess the dynamics of competitiveness using artificial intelligence. This requires, based on an understanding of the doctrine of the organization of theoretical and practical human activity, to develop a methodology for solving the tasks following the set goal. The main idea is to implement a method for structuring a large number of indicators of socio-economic activity of the regions of the Russian Federation available for analysis in the corresponding cyber-physical system. Let this structuring be based on hierarchical structures. In them, the leaves of the tree will be the statistical indicators of socio-economic activity from the official statistics [12, 13]. Further, we will combine using specially developed integral indicators [14, 15].

The development of the proposed mathematical model is based on analogies of quantum-electric wave functions and membership functions of the theory of fuzzy sets. For individual social processes, the new method of status functions (SF) [16] was well demonstrated, which allows one to take into account the intersection and mutual influence of individual indicators.

3 Characteristics of Methods for Analyzing Networks of Socio-Economic Indicators

Thus, a causal graph of indicators can be obtained. The analysis of this graph can be carried out by methods of constructing minimal sections of the Kolmogorov-Chapman equations [15]. Based on such graphs, networks of socio-economic indicators can be built. Let's define them as a set of relevant nodes connected by one or more relations [17]. The relations of connections of leaf vertices will be determined based on specially synthesized indicators. For example, if statistical data is available on indicators in the constituent entities of the Russian Federation:

- the number of researchers with a scientific degree;
- internal costs for research and development;
- the level of innovative activity of organizations;
- the volume of innovative goods, works, services,
- Let's combine them into an indicator:
- indicator of innovation.

Then we will form a set of indicators. The significance of these indicators is different; accordingly, their connections in the system are also different. Let us construct the links between the indicators of the competitiveness of the region for the CFS by analogy with computer networks. Then topologies such as star, bus, mesh, fully connected mesh, tree, combined topologies will be possible. In addition, the graph may not be connected, it may contain isolated vertices and networks of vertices of different topologies.

First, you need to analyze the interaction of indicators. Such an analysis is possible based on four main approaches [18–20]:

1. Structural approach (or formal-mathematical). Based on the analysis of the geometric shape of the network and the intensity of interactions between nodes. In our case, the analysis of the competitiveness of the region is initially lacking. Therefore, for the formed network, it is not advisable to focus on such methods

of analysis, in which special attention is paid to the mutual arrangement of vertices, centrality, and transitivity of interactions.

2. The resource-based approach considers the possibilities of interaction participants, as network nodes, to attract network resources to achieve certain goals. At the same time, the nodes located in identical structural positions of the social network are differentiated according to their resources (influence, status, information, capital).
3. The normative approach studies the norms and rules that affect the processes of interactions between network nodes.
4. The dynamic approach focuses on changes in the structure of the network over time.

If we focus on a dynamic approach, then it is possible to create a network of parameters based on the opinions of experts, and then conduct a study of its transformation. The resource-based approach will allow you to create complex structures based on status functions. However, you first need to build a network prototype for use in a cyber-physical system.

4 Description of the Network Preimage

Let's try to rebuild the causal graph into a network structure. We will be based on the indicators of the leaf vertices of the causal graph presented in [15]. For them and their groups, we used the notation Ei from [15]. For the groups created for the network graph, in this work, we use the notation Qi.

Group–1 (q1): the use of fixed assets (E9) includes:
the cost of fixed assets q11 (E29); depreciation rate of fixed assets q12 (E30).
Group–2 (q2): the development of transport infrastructure (E10) includes:
the density of railway tracks q13 (E31); road density q14 (E32).
Group–3 (q3): the income level of the population (E11) includes:
per capita money income q15 (E33); population with incomes below the subsistence level q16 (E34); the number of officially unemployed people q17 (E35).
Group–4 (q4): demographic (E12) includes:
life expectancy q18 (E36); population growth rate q19 (E37); the coefficient of migration growth q20 (E38).
Group–5 (q5): quality of life q21 (E13) includes:
dilapidated and dilapidated housing q22 (E39); the number of doctors per 10,000 population q23 (E40); the number of registered crimes q24 (E41).
Group–6 (q6): natural resources (E5) includes:
mining q25 (E14); agricultural land area q26 (E15); availability of forest resources q27 (E16); electricity production q28 (E17); emissions of polluting products q29 (E42); discharge into water bodies of polluted wastewater q30 (E43).
Group–7 (q7): institutional (E6) includes:

share of unprofitable organizations q31 (E19); arrears of taxes and duties q32 (E20); business income q33 (E21).
Group–8 (q8): informational (E7) includes:
the number of personal computers q34 (E22); Internet use in organizations q35 (E23); use of electronic document management systems in organizations q36 (E24).
Group–9 (q9): innovative (E8) includes: personnel engaged in research and development q37 (E25); internal expenditure on research and development q38 (E26); costs of technological innovation q39 (E27); the volume of innovative goods q40 (E28).

At the initial stage, we will assume that the listed groups of exponents q1 $\div$ q9 have the same mutual influence, respectively, have the topology of a fully connected mesh.

In addition, we introduce the vertex q10—representing the competitiveness of the region and assume that it is connected with all vertices q1 $\div$ q9. Each of the vertices q1 $\div$ q9 is associated with the vertices, which are "leaf" and described by controlled indicators, the data of the values of which are obtained from the statistics [21]. Each of the vertices q1 $\div$ q9 forms a star topology for the associated "leaf" indicators.

Figure 1 shows the result of the transformation of the causal graph obtained for the analysis of the competitiveness of the regions of the Russian Federation by the methods of solving the Kolmogorov-Chapman system of differential equations for use in the CFS.

5 Interpretation of Status Functions in Graph Nodes

We will interpret the status functions (SF) in leaf vertices for the following reasons.

1. For "leaf" tops. Here SF is a complex-valued function. The SF amplitude is determined based on official statistics [12, 13]. The following assessment levels are possible:

    (a) low–medium–high;
    (b) bad–satisfactory–good–excellent;
    (c) low–below average–average–above average–high.

An orthonormal function is assigned to them. These functions are similar to the "pure states" functions in quantum mechanics. However, in our case, these functions will initially be mixed, since, depending on the numerical range of measurement of the indicator of the socio-economic activity of the region, one of three possible levels of assessment can be selected. Therefore, the result based on the orthonormal functions will immediately be mixed.

Let's say the probabilities of their changes can be interpreted as membership functions. Let us normalize the membership functions using the Gram-Schmidt methods

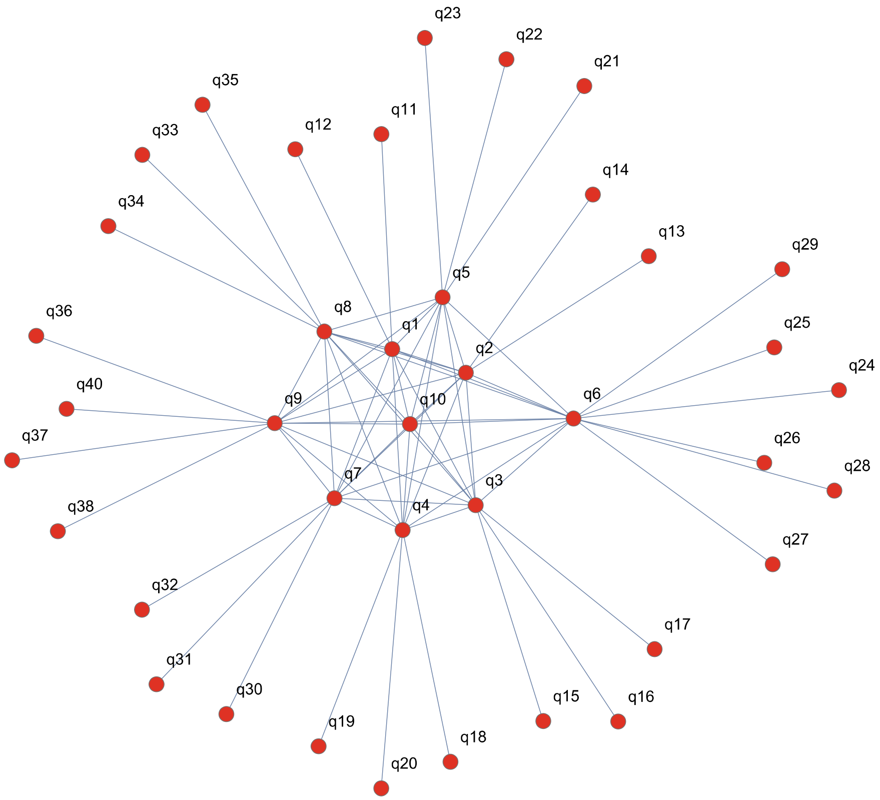

Fig. 1 Transformation of the causal graph of the competitiveness of the region [15] into a network graph that is not a state graph

and obtain sets of orthonormal alternating functions. These alternating functions can represent an analog of the probability of realizing the observed value. They can be assigned to the corresponding state by analogy with membership functions. In addition, they are orthonormal and can be used as an analog of quantum mechanical functions of pure states.

The complex part $e^{2\pi ikr}$ is formed from a comparison of the trend over the last 3 years. A steady tendency towards a deterioration in the indicator k = −1, a slight deterioration in k = −0.33, no change in k = 0, a slight deterioration in k = 0.33, a steady tendency toward an improvement in the indicator k = 1.

Let's say that when evaluating states, 3 possible values are used: low–medium–high.

$$\psi_{low} = 3.37619(e^{-50.(\mathrm{r}+0.14)^2} - 0.580252e^{-22.2222r^2}; \quad (1)$$

$$\psi_{average} = 1.9394e^{-22.2222r^2}; \quad (2)$$

$$\psi_{high} = 1.37668e^{-(14.-50.r)r} + 1.87105e^{(14.-50.r)r} - 5.02117e^{-22.2222r^2}. \quad (3)$$

The complex part sets the direction of displacement of the mean value in r. The basic variable r introduced by analogy with the theory of fuzzy sets characterizes the space of mixing or mutual influence of exponents.

Let's introduce time dependence. Let's say it is similar to the time dependence of the Cobb–Douglas production function [22, 23]. However, the task is to form an oscillatory function similar to a quantum mechanical function. Then it is logical to expect a time dependence somewhat different from the Cobb–Douglas model. We represent it in the form $e^{-i\varepsilon t}$, where ε is some constant.

Thus, let us assume that a certain parameter of the system of parameters of the competitiveness of a region can be represented by a status function, which is measured when collecting statistical data. Moreover, SF is in a sense analogous to the wave function of "pure states" of a quantum mechanical particle. This function for a free quantum mechanical particle can be represented as:

$$f(r, t) = C(t)\psi(r)e^{-(i\varepsilon t - 2\pi kr)}, \quad (4)$$

where r is a coordinate in a certain space, t is time, $C(t)$ is the dependence of the amplitude on time, $\psi(r)$ is the characteristic of the maximum of the SF in the space of mixing parameters, ε is some constant, k is the characteristic associated with the "momentum" of the investigated object. The particle energy is proportional to $k2$. Thus, its approximate form can be obtained from the equation of flows.

2. For integral indicators q1 ÷ q10. Each of the vertices q1 ÷ q9 is associated with vertices that are "leaf" and described by controlled indicators, the values of which are obtained from the statistics [21]. Therefore, the variables q1 ÷ q9 must be obtained from the indicators included in them. The value of the q10 exponent should be obtained from the set of q1 ÷ q9 exponents. Let's start forming them based on a mathematical model.

6 Development of a Mathematical Model for Assessing the Competitiveness of Regions

We design equations for integral indicators based on optical-electrical analogy. We proceed from the put forward assumption that each controlled indicator changes according to some complex harmonic law. This idea is fully consistent with modern ideas of cyclical oscillatory processes in the economy [24].

Let the competitiveness of the region be a complex value and depend on itself according to the law of Malthus. The limitation is associated with its complex part. The competitiveness is positively influenced by managerial influence. This can also be considered a hypothesis since it can be proved that it is the managerial influence that positively affects the growth of competitiveness. A negative impact is also possible. Let us assume that the managerial influence has a positive effect.

Let instead of competitiveness in the right side of the equation be used its dependence on the sum of its 9 intermediate indicators. Each of these indicators is represented by an integrodifferential equation for the integral indicator itself, which on the right side of the equation will be used as the sum of an unknown indicator and its particular value, represented by a polynomial. The polynomial is obtained as a result of interpolation of real statistical data describing the leaf indicators of the graph in Fig. 1. At the same time, for each of the intermediate indicators included in the structure of the causal graph, indicators have been used that form its branch. For example, for the intermediate integral indicator "Innovative", the sheet indicators "The number of researchers with a scientific degree in the constituent entities of the Russian Federation", "Internal expenditures on research and development by the constituent entities of the Russian Federation", "The level of innovative activity of organizations", "The volume of innovative goods, works, services"(see Fig. 2).

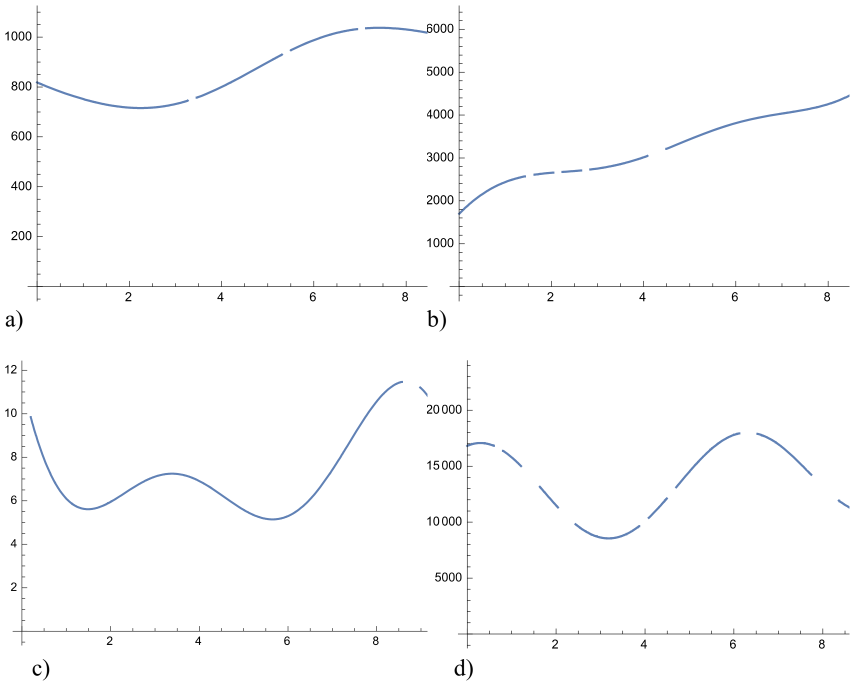

Fig. 2 The dots represent the normalized values of the indicators **a** the number of personnel engaged in research and development q_{37}; **b** internal costs for research and development q_{38}; **c** costs of technological innovations q_{39}; **d** the volume of innovative goods q_{40} obtained from the data [13] for the Saratov region for the period 2010 $\div$ 2019, the solid line—the results of interpolation of statistical data

Thus, we will begin to form a system of equations for assessing the competitiveness of the region.

For root node q10:

$$\frac{df(t)}{dt} = \alpha\left(i\beta\sum_{j=1}^{9} q_j(t) - \sum_{j=1}^{9} q_j(t) + p(t)\right). \tag{5}$$

For intermediate nodes of the first level, which are the consequences of causes $q_1 \div q_9$:

$$\frac{dq_k(t)}{dt} = \alpha\left(i\beta\left(q_k(t) + \int_{-1}^{1}\left(\sum_{i=1}^{k} q_i(t)\psi_j(r)\right)dr + polimom_k(t)\right) - q_k(t) - \int_{-1}^{1}\left(\sum_{i=1}^{k} q_j(t)\psi_j(r)\right)dr - polimom_k(t) + p(t)\right). \tag{6}$$

Let's add managerial impact:

$$\frac{dp(t)}{dt} = \gamma(i\delta p(t) - p(t) + w(t)f(t)), \tag{7}$$

Let's introduce a description of the socio-economic environment:

$$\frac{dw(t)}{dt} = \chi(A - w(t) - \frac{1}{2}\big(f^*(t)p(t) + f(t)p^*(t)\big), \tag{8}$$

where $f(t)$ is the SF for the integral indicator of the region's competitiveness q10, qk are the functions for each of the integral indicators q1 ÷ q9, $polimom_k$ is the polynomial obtained as a result of the interpolation of statistical data for the period 2009 ÷ 2019, $p(t)$—F, characterizing the management impact, $w(t)$—SF, describing the environment in which the region operates, α—the rate of relaxation of the student to the initial state, β—the coefficient of the interaction of control with the controlled system, γ—the rate of reflection and recovery of the management system for the possibility take managerial influences, δ is the coefficient of the interaction of the control system with the controlled, χ is the rate of recovery (relaxation) of the environment, A is the characteristic of the threshold state of the socio-economic environment, *—denotes the symbol of complex conjugation.

7 Analysis of Numerical Simulation Results for Leaf Vertices

Consider an example of the formation of an SF for leaf vertices for one of the groups of parameters innovative (q9). Let us assume SF in the form (4). Here are the normalized values of statistical data for the Saratov region. Based on statistical data (Table 1), we construct $polimom_k(t)$ (Fig. 2). The characteristic of mixing indicators has three possible values (1) ÷ (3) and the corresponding form of the function is shown in Fig. 3. The direction of the bias trend is set by possible values that are obtained from comparison with data from other regions of the corresponding cluster and may have the following values: "High values of the indicator, it has been growing for the last 3 years, more than 10% higher than the same indicator for neighboring regions", "High values, changes within 3 years within the margin of error", "High values of the indicator, growing for the last 3 years." For them, k = −1, k = 0, k = +1.

Let's interpolate the data in Table 1 and get the following expressions:

Table 1 Values of indicators of the group of parameters "Innovations"

Indicator/year	Number of personnel engaged in research and development q37	Internal expenditures on research and development q38	Expenditures on technological innovations q39	The volume of innovative goods q40
2010	729	2365,275	6,4	17,222,125
2011	753	2693,1602	5,5	7713,7124
2012	741	3020,6738	7	10,617,418
2013	823	2843,242	6,4	13,180,746
2014	778	3298,273	6,8	8484,9
2015	1055	3577,7	6,3	23,177,377
2016	1067	4387,7	4,8	16,065,337
2017	994	4464	11,794,872	10,348,813
2018	1014	4484,3	11,157,718	12,833,643
2019	939	6209,6	6,1	13,457,747

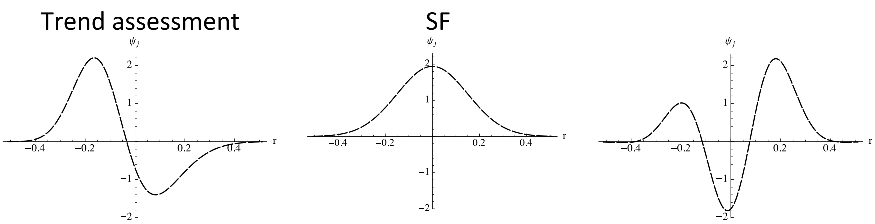

Fig. 3 Type ψ (r) for low, medium and high values of the linguistic term of assessment

For q_{37} $$polimom_{37} = 655.127e^{-0.1t} + 32.1817e^{-it} + 32.1817e^{it} - i\,274196e^{-0.1it} + i\,274196e^{0.1it} + i\,139778e^{-0.2it}i - 139778e^{0.2it}. \quad (9)$$

For q_{38} $$polimom_{38} = -46479.8e^{-0.1t} + 169.581e^{-it} + 169.581e^{it} + i\,1.0824410^{7}e^{-0.1it} - i\,1.0824410^{7}e^{0.1it} - i\,5.5018510^{6}e^{-0.2it}i - i\,5.5018510^{6}e^{0.2it} + 47838.5e^{-0.001t}. \quad (10)$$

For q_{39} $$polimom_{39} = 4899e^{-0.1t} - 537.115e^{-it} - 537.115e^{it} - i\,3.3794310^{6}e^{-0.1it} + i\,3.3794310^{6}e^{0.1it} + i\,1.7132210^{6}e^{-0.02it} - i\,1.7132210^{6}e^{0.02it}. \quad (11)$$

For q_{40} $$polimom_{40} = 1436.1e^{-0.1t} + 2226.6e^{-it} + 2226.6e^{it} + i4.2903510^{6}e^{-0.1it} - i\,4.2903510^{6}e^{0.1it} - i\,2.1268810^{6}e^{-0.02i} + i\,2.1268810^{6}e^{0.02it}. \quad (12)$$

8 Conclusions

Thus, it is possible to put forward a hypothesis about the possibility of adding a factor in the form of e^{-it} to SF [16]. This dependence can be traced from the interpolation results. The function is dependent on the total energy of the system, which cannot be obtained from a single parameter. At a minimum, it is necessary to form a complete system of monitored indicators, but this is not enough. It cannot be guaranteed that the list of monitored indicators fully describes the system of competitiveness of the region of the Russian Federation. Or, for a complete system of all regions, this system will also be approximate, since in reality the system is open and exchanges, like a cyber-physical system, energy with the environment. Thus, at the present stage of modeling the competitiveness of Russian regions, it is necessary to agree with the approximate representation of energy. The undoubted advantage of the model is the assumption that the system has energy.

Secondly, you need to decide: what data is available for analysis? Data collection was carried out based on databases such as the Russian Statistical Yearbook, Socio-economic indicators [21], and IAS "FIRA PRO". As a result, information and analytical base for further research have been developed, which is characterized by the use of data structures with the systematization of indicators in a chain of cause-and-effect events and combining them into integral indicators of CPS, which made it possible to use this information in the developed methods of algorithmic data analysis with a focus on creating an intelligent information system. identifying risks associated with maintaining and developing regional competitiveness.

Third, a complex system has been obtained; therefore, it is advisable to use it for fragmentary analysis. In this regard, a methodology, algorithms, and mathematical models have been developed based on the Kolmogorov-Chapman, Cobb–Douglas equations, equations of the dynamics of quantum generators, and optical-electrical analogy.

Such a complex transformation, based on preliminary assessments of competitiveness based on the Kolmogorov-Chapmen equations, proceeds from the understanding that Markov processes are considered in the systems of Kolmogorov-Chapman equations. In practice, the evaluation of Markov chains is a trade-off between increasing the number of observations to obtain reliable estimates and increasing the probability of violation of the Markov property. When we strive to improve accuracy, we are forced to abandon the used model. However, without the initial model, it is impossible to develop mathematical models intended for the development of methodological and analytical tools for assessing the dynamics of the risks of competitiveness of Russian regions using artificial intelligence for CPS. The development of the model is based on analogies of quantum-electric wave functions and membership functions of the theory of fuzzy sets. For individual social processes, the new method of status functions was well demonstrated, which allows one to take into account the cross-section and mutual influence of individual indicators. Modification of the Kolmogorov-Chapman equations is carried out to use status functions to assess individual indicators.

Thus, the possibility of using numerical methods of nonlinear dynamics for analyzing the competitiveness of regions of the Russian Federation is shown, which is distinguished by the use of the method of status functions, which made it possible to take into account the intersection and mutual influence of parameters of competitiveness risks for use in cyber-physical systems. Original methods have no analogs in modern literature. The results of the work are intended for use in the development of mathematical models of advising systems for monitoring and countering the disruption of the stable functioning and development of regions of the Russian Federation using modern mathematical models and information technologies in the CFS [25–27].

As a result, a description of the temporal and logical structure of tools for assessing the dynamics of competitiveness risks were obtained, statistical data were collected and structured, mathematical models were tested, which served as the basis for programs for the further development of methodological and analytical tools for assessing the dynamics of competitiveness risks using artificial intelligence for the corresponding CPS.

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Multi-level Management of Organizational Systems on the Basis of Risk Cascading, Logical-Probabilistic Modeling and Simulation

Irina Bondareva and Anna A. Khanova

Abstract A conceptual solution allows for multi-level risk management of an organizational system (for example, a cargo port) is presented. A step-by-step mechanism for the integrated use of risk cascading and Logical-Probabilistic modeling is proposed for a detailed and multifaceted description of cause-and-effect relationships, as well as simulation modeling as a tool for analyzing, assessing, and predicting the onset of risk situations. The described mechanism is displayed in the form of a structural diagram of multilevel risk management. The method for cascading risks at the strategic, tactical, and operational levels of management is described in detail. Each level considers as a risk situation failure to achieve goals, failure to achieve target performance assessment indicators of standard values, and failure to achieve detailed targets for assessing target implementation of standard values, respectively. A cascade logic-probabilistic model of the risk of failure to achieve the strategic goal of a cargo port is presented, detailing the scenarios of the first level of goal-setting and including all three levels of management. The logical and probabilistic models of various levels of management are formulated and described, the identified basic regularities are explained. The mechanism for fixing the onset of risk situations at the operational level using cascading and simulation technologies, identifying cause-and-effect relationships using logical-probabilistic modeling, as well as formulating recommendations to prevent the onset of risk situations in future periods is described in detail, i.e. at the tactical and operational levels of management.

Keywords Risk cascading · Logical-probabilistic modeling · Simulation modeling · Multilevel management

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1 Introduction

Studying the issues of effective technologies for managing enterprises, which are, thanks to a large number of interacting business processes, a complex organizational system (OS), today is associated with the identification, as well as a comprehensive analysis of goals, indicators of their achievement, as well as risks. Building logical relationships between planning and assessing the likelihood of the onset of the possibility of performing an urgent task, a promising and justified possibility of increasing the efficiency of management [1–11].

An approach using logical-probabilistic (LP) modeling [1, 2, 6, 7, 11] is used as a modern toolkit for describing this kind of relationship. One of its advantages is the ability to consider aspects of activities not only from the point of view of economic efficiency but also with a focus on the interests of all parties involved in this process.

Along with LP-modeling to trace the cause-and-effect relationships when a risk situation occurs, it is proposed to use the mechanism for representing the hierarchy of goals and indicators in the form of cascades [12–17].

Cascading initially appeared as a tool for specifying goals and indicators for assessing the performance of certain enterprises by specifying general performance criteria for specific divisions. Thus, the responsibility and contribution of each specialized division to the overall strategy of the enterprise are indicated in accordance with the specifics of the work carried out by it. That is, cascading allows you to formulate and clarify goals and indicators for more detailed and consistent tracking of possible deviations from the intended goals from the moment of their occurrence in order to adjust the functionality of the responsible units before correcting an unfavorable situation.

The analysis of the sources devoted to the cascading of goals and indicators allows us to judge its use in most cases in conjunction with a balanced scorecard, which is a strategic management tool [11, 12, 15]. Much more popular and justified in practice is the technology for implementing multilevel management—from strategic to tactical and operational and vice versa. That is an approach in which all strategic goals are subordinated to the evaluative mechanism for maintaining the overall strategy through the implementation of detailed goals at the tactical and operational levels. A description of this mechanism concerning the organization's risks was not found, and therefore the purpose of the work is to form a structure for multi-level management of organizational systems by the joint use of organization risks cascading and LP-modeling [14–21].

2 Risk Cascading

Multilevel cascading of risks consists in the formulation of the main strategic goal and its detailed goals at the strategic management level, where failure to achieve goals is considered as a risk. Then, at the tactical level of management, for each goal,

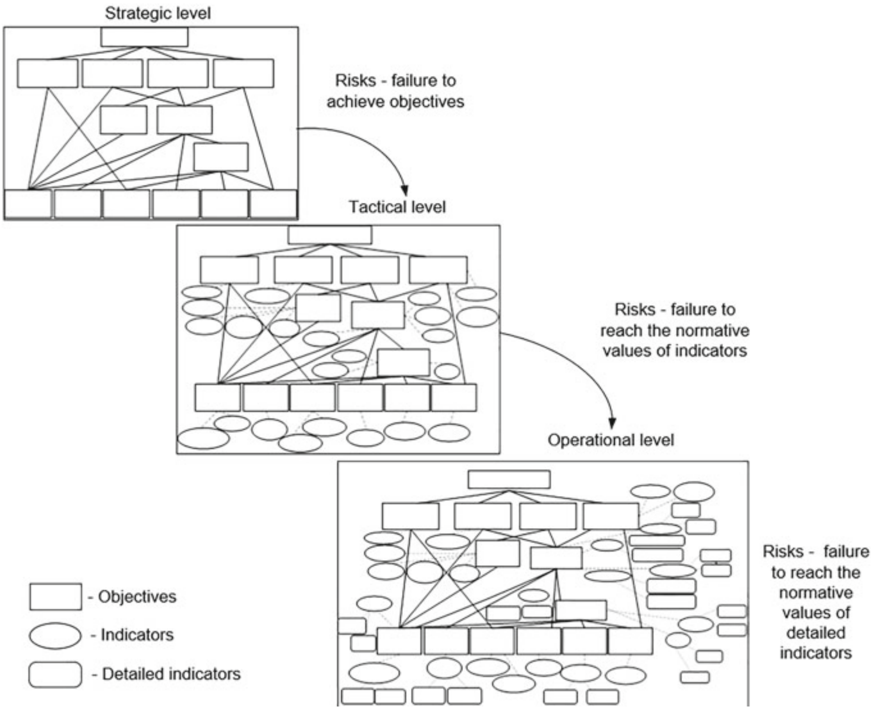

Fig. 1 Scheme of cascading risks

the indicators that evaluate it are formulated, and the failure of the indicators to assess the implementation of the goals of the standard values is already used as risks. The operational level of management complements the tactical detailed indicators for assessing the achievement of goals, i.e. breaks down several indicators of the tactical level, specifying them according to various criteria: concerning the structural units responsible for the achievement of the indicator of the normative value; concerning the type of work performed or services provided, etc. At the operational level, risks are the failure of detailed indicators to assess the achievement of targets of standard values. Risk cascading is shown schematically in Fig. 1.

3 Multi-level Risk Management Based on Cascading Risks

It is possible to calculate the detailed indicators for assessing the achievement of goals formulated at the operational level (block 1 “Cascading risks”) using simulation (block 2 “Simulation model”) [7, 10, 11]. Based on the results of simulation experiments, report statistics are generated, based on which a summary table of risk assessment is built, thus, deviations from the standard values of detailed indicators for

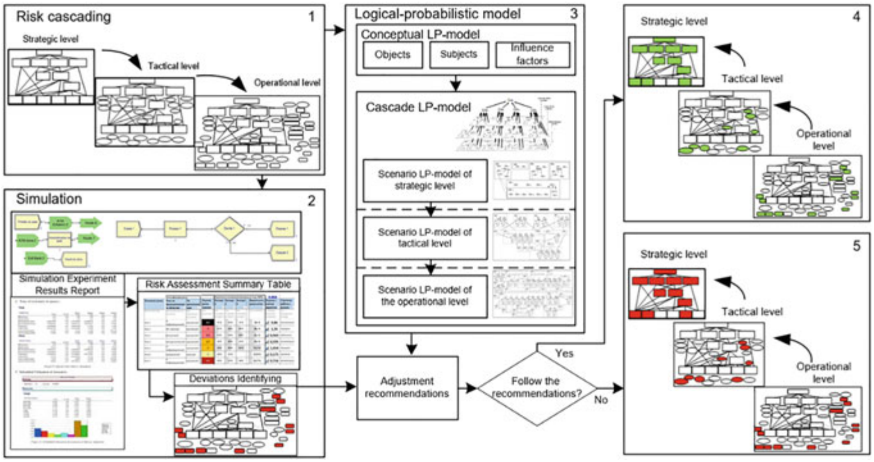

Fig. 2 Block diagram of multi-level OS risk management based on cascading risks, LP-model, and simulation

assessing the achievement of goals are revealed, i.e. possible operational level risks. Based on this information, taking into account the identification of cause-and-effect relationships of the LP-model (block 3), recommendations are developed to prevent the identified risk situations. Taking into account such recommendations allows you to adjust the values of detailed indicators at the operational level by influencing the objects of the system under consideration, which in turn favorably affects the elimination of risk situations at the tactical and strategic levels, i.e. allows you to achieve strategic goals in the future (block 4). On the contrary, ignoring recommendations for adjusting the behavior of the system negatively affects the risks of subsequent periods, provoking their inevitable onset (block 5). Consider the described integration of the proposed approaches for multilevel risk management of an organizational system (Fig. 2). As a subject area, we have chosen a transport logistics enterprise—a cargo port [13, 18, 19].

4 Logical-Probabilistic Modeling

The LP-risk model is a set of conceptual models that describe the relationship between OS objects (targets), subjects, and factors of influence [7, 22, 23].

For multilevel risk management, it is of greater interest to identify causal relationships presented on the cascade LP-model (Fig. 3), reflecting scenario LP-models of all three levels of management. Objectives $G_{ccp} = (GN_1, GN_2, \ldots, GN_4)$ correspond to the LP risk models. Objects-targets are the components of Gccp: GN_1—to reduce dependence on external loans, GN_2—to increase the efficiency of resource use, GN_3—to increase the level of corporate social responsibility, GN_4—to increase profitability

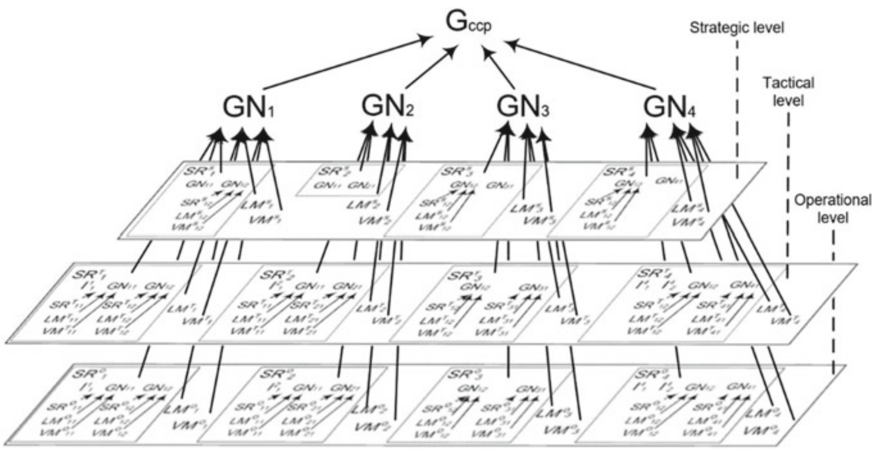

Fig. 3 Cascade LP-model of the risk of failure to achieve the strategic goal of the OS (detailed scenarios of the first level of goal-setting, three levels of management)

and solvency. According to the concept of using LP risk models for each i-th goal GN_i, it is necessary to sequentially construct a risk scenario SR_i, L-model LM_i, and P-model VM_i. Figure 3 shows scenarios of the first level of goal-setting, including the following elements: GN_{11}—to improve the qualifications of employees, GN_{12}—to increase the level of responsibility to consumers, GN_{21}—to optimize the number of port resources, GN_{31}—to increase the level of social protection of personnel, GN_{41}—to ensure the stability of sales, $I_1{}^1$—return on assets, $I_1{}^2$—the ratio of financial independence, $I_1{}^4$– the ratio of absolute liquidity, $I_2{}^4$—the ratio of return on equity.

At the strategic level, the logical model LM Sccp of event failure takes the form: $G_{ccp} = GN_1 \vee GN_2 \vee \ldots \vee GN_4$.

Probability function (P-model) VM S_{ccp} of event failure:

$$\begin{aligned} P\{G_{ccp} = 0\} = & P\{GN_1 = 0\} + P\{GN_2 = 0\}(1 - P\{GN_1 = 0\}) + P\{GN_3 = 0\} \\ & (1 - P\{GN_l = 0\})(1 - P\{GN_2 = 0\}) P\{GN_4 = 0\}(1 - P\{GN_1 = 0\}) \\ & (1 - P\{GN_2 = 0\})(1 - P\{GN_3 = 0\}). \end{aligned}$$

The logical and probabilistic models of the first level of goal-setting at the operational level will be identical to the corresponding models of the tactical level. This is because the scenarios of the first level of goal-setting of the operational level of management did not change relative to the tactical level. After all, they contain indicators that are not detailed by any criteria (indicators of the first level). That is why the following is true.

$$LM^o = LM^T_{ccp} : G_{ccp} = I_1^1 \vee I_1^2 \vee GN_3 \vee I_1^4 \vee I_2^4.$$

$$VM^o_{cp} = VM^T_{ccp}:$$
$$P\{G_{ccp} = 0\} = P\{I^1_1 \neq I^1_{1norm}\} + P\{I^2_1 \neq I^2_{1norm}\}(1 - P\{I^1_1 \neq I^1_{1norm}\})$$
$$+ P\{GN_3 = 0\}(1 - P\{I^1_1 \neq I^1_{1norm}\})(1 - P\{I^2_1 \neq I^2_{1norm}\})$$
$$P\{I^4_1 \neq I^4_{1norm}\}(1 - P\{I^1_1 \neq I^1_{1norm}\})(1 - P\{I^2_1 \neq I^2_{1norm}\})$$
$$(1 - P\{GN_3 = 0\})(1 - P\{I^4_1 \neq I^4_{1norm}\}).$$

The remaining levels of goal-setting are represented by goals GN_{121}—increase the level of environmental protection, GN_{122}—increase the level of interaction with local authorities, GN_{123}—improve the quality of loading and unloading operations, GN_{1231}—timely execution of loading and unloading operations [24]. A complete list of indicators for assessing achievement with an indication of the criteria for their detailing (if any) at the operational level is presented in Table 1.

As the structural subdivisions of the port within the framework of this study, we will take the following: cargo operations department, warehouse complex, commercial department, tally department, technical department, supporting departments, and port management. The following are considered as interesting types of services provided by the port: transshipment of goods, storage of goods, freight forwarding by rail, and road transport. The considered cargo port carries out the loading of the following types of cargo: sand, asbestos, sheet iron, and iron channel.

Let us consider, for comparison, the scenario models of the risk of failure to achieve the strategic goal of the cargo port of the tactical (Fig. 4) and operational (Fig. 5) management levels, including all levels of goal-setting [6, 7, 10, 11].

A visual comparison of the tactical and operational level scenarios allows us to make sure that the operational level scenarios extend the tactical level scenarios by including new scenarios of detailed indicators that have a direct impact on the corresponding elements of the scenario of the previous goal-setting level. At the operational level, the failure of an event may be evidenced by the failure of at least one of the indicators detailing it according to the selected criterion (Tab. 1) indicators of its normative value.

As an example, consider the LP-model of the complex indicator I_1^{12} "Number of regular customers", detailed at the operational level by type of service (transshipment, storage, and forwarding of goods) on I_1^{121}, I_1^{122},and, I_1^{123} respectively.

$$LM_{1^o12} : I^{12}_1 = I^{121}_1 \vee I^{122}_1 \vee I^{123}_1.$$

$$VM^o_{112}:$$
$$P\{I^{12}_1 \neq I^{12}_1 norm\} = P\{I^{121}_1 \neq I^{121}_1 norm\} + P\{I^{122}_1 \neq I^{122}_1 norm\}$$
$$(1 - P\{I^{121}_1 \neq I^{121}_1 norm\})\ P\{I^{123}_1 \neq I^{123}_1 norm\}$$
$$(1 - P\{I^{121}_1 \neq I^{121}_1 norm\})(1 - P\{I^{122}_1 \neq I^{122}_1 norm\}).$$

Table 1 Cargo port performance indicators and criteria for their detailing

Indicator symbol	Indicator, units	Indicator detail criterion
$I_1{}^1$	Return on assets	–
$I_2{}^1$	Financial independence ratio	–
$I_1{}^4$	Absolute liquidity ratio	–
$I_2{}^4$	Return on equity ratio	–
$I_1{}^{11}$	Percentage of employees whose qualifications are appropriate for the position held, %	Structural units
$I_2{}^{11}$	Employee training costs, cu	Structural units
$I_1{}^{12}$	Number of regular customers, units	types of services
$I_2{}^{12}$	Percentage of repeat clients, %	Types of services
$I_3{}^{12}$	Number of new clients, units	Types of services
$I_4{}^{12}$	Number of dissatisfied customers, units	Types of services
$I_1{}^{21}$	Equipment intensive use ratio	–
$I_2{}^{21}$	Equipment extensive use ratio	–
$I_1{}^{31}$	The number of tax deductions for the period, cu	–
$I_2{}^{31}$	The volume of social contributions for the period	–
$I_3{}^{31}$	The ratio of the minimum wage to the cost of living	–
$I_4{}^{31}$	The ratio of the minimum wage to the average, %	–
$I_1{}^{41}$	Provision with orders (contracts) in days, day	–
$I_1{}^{121}$	The proportion of ships meeting environmental standards, %	Types of cargo
$I_1{}^{123}$	Reliable loading, %	Types of cargo
$I_2{}^{123}$	THe amount of lost (damaged) when loading cargo, t	Types of cargo
$I_3{}^{123}$	Average loading time, h	Types of cargo
$I_1{}^{1231}$	Percentage of loading works completed on time, %	Types of cargo

5 Conclusion

A distinctive feature of the proposed mechanism is the ability to predict the occurrence of undesirable situations in subsequent periods at the operational stage of management, i.e. at other levels of government. Predictions of a similar nature by monitoring the corresponding values of risks of failure to achieve goals and standard values of indicators make it possible to develop recommendations for adjusting the values to prevent negative risk situations in future periods. It is this multilevel approach to management that will result in the achievement of the set strategic goals and, thus, lead the organization to consistently effective development.

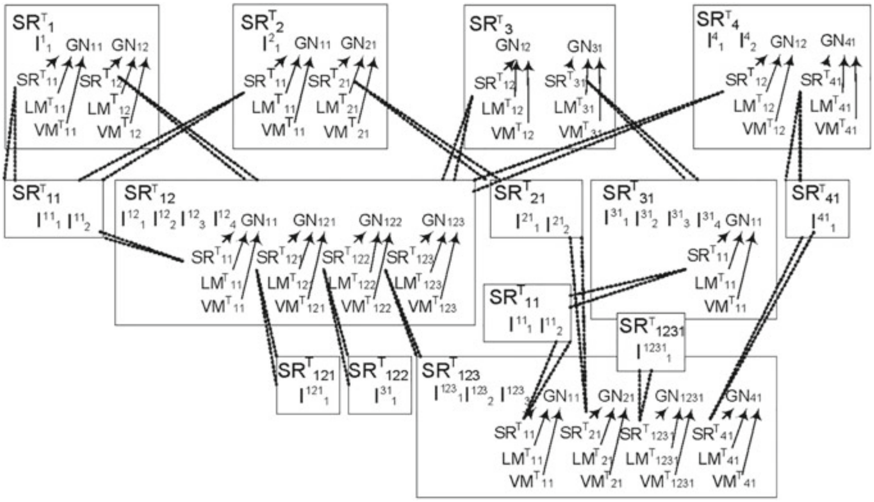

Fig. 4 Model of tactical scenarios of risks of failure to achieve goals associated with the main strategic goal of the cargo port

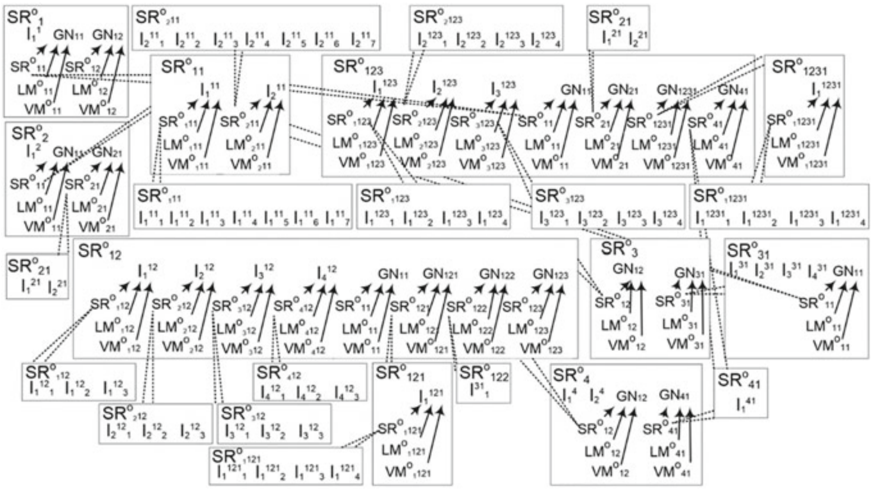

Fig. 5 Model of operational scenarios of risks of failure to achieve goals associated with the main strategic goal of the cargo port

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Principles for Modeling Information Flows in Open Socio-Economic Systems

Aleksandr Davtian, Olga Shabalina, Natalia Sadovnikova, Olga Berestneva, and Danila Parygin

Abstract Modern socio-economic systems exist and function being inevitably immersed into the information space. When modeling management in such systems there is a need for a formalized representation of the information flows providing the interaction of the system with its environment. The chapter discusses the principles of modeling information flows in open socio-economic systems considered as determining the impact of the environment on socio-economic systems and the impact of the systems on the environment, and, thus, form the state of the socio-economic system. The resources transferred by the environment to the system for the execution of its mission are considered input information flows, the output flows are formed as the transfer of the results of the system's activities demanded by the environment. The ways of correlating the influence of information flow on the state of the system, chosen by people, and, thus, not reducible to functional dependencies, are modeled as "thinking" functions. An open socio-economic system is considered as a form of interaction of the environment with itself, and the proposed principles for modeling information flows reflect the dualism of the relationship between the system and the environment.

Keywords Open socio-economic system · Management in socio-economic systems · Model of an open socio-economic system · Information flow · Information flows modeling

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1 Introduction

Modern socio-economic systems exist and function being inevitably immersed into the information space. The successful functioning of any socio-economic system (SES) requires constant monitoring and analysis of information flows that ensure the influence of the environment on the system and the influence of the system on the environment [1–3].

When modeling management in socio-economic systems immersed in the information environment there is a need for a formalized representation of the information flows for modeling the interaction of the system with its environment.

2 Approaches to Modeling Information Flows in Socio-Economic Systems

In a number of studies information flows are distinguished by the types of information sources that generate these flows (e.g. financial flows [4, 5], cash flows [6, 7], sales management flows [8], logistics flows [9–11]). In [12] the authors consider information flow as "a key variable in system safety" and underline the role of information in causing or preventing technological accidents [13]. In [12], the optimal informational flow model is introduced and its applicability to assess predictive causality by extracting predictive causal networks of complex ecosystems is considered. Information flow study related to the problems of SES safety is presented in [14], modeling causal interactions for predictability of ecosystem management [15].

But for modeling the behavior of SES operating in the information environment, there is a need for a formalized representation of information flows, abstracted from information sources [16]. Information flow models are proposed in a number of studies [17]. In [18], an input information flow model is proposed, represented by a set of elementary information fragments, which are considered as a pertinent part of various information documents. Information flows are represented as Poisson processes; the information processing planning task is modeled within the queuing theory. The model is proposed to be applied to reduce the influence of information noise on the quality of the information processing process.

In [19] information flows are considered as a set of semantically related elements (documents) that form an information space in the dynamics of their evolution. Information flows are modeled as time series, for the analysis of which correlation analysis, variance analysis, fractal analysis, wavelet analysis are used. To represent semantic properties, the concept of a thematic information flow is introduced as a sequence of messages corresponding to a specific topic. The developed model is proposed for solving problems related to automatic text processing.

The model of information flows of logistics processes at the enterprise, proposed in [20], is represented by a set of project documents. The model is based on formalized descriptions of text, tabular and graphic documents describing information flow schemes, information about external objects, data stores, and other characteristics of logistics processes. As information flows, both information flows within the system and flows between the system and its environment are considered [21].

In [22], methods of modeling information flows in the context of the organization of management in SES are considered. An information flow model distinguishes the discrete processing stages within the process, describes how information flows through that system, characterizes the kinds of data items that flow through the process, and captures the type or method of data access. Depending on the formalization approach, two categories of models of information flows are distinguished—diagrammatical and mathematical models. Pictorial, matrix, and graph models are considered as diagrammatical models, agent-based models, system dynamics models, discrete-event models are referred to as mathematical models. Depending on the level of accessibility and use of information, information flows are considered as belonging to the macro-, meso- and micro-levels. Information flows at the macro-level model the environment of the system.

3 Model of an Open Socio-Economic System

In the considered models the information flows inside the system (the internal flows) are considered as the main flows determining the functioning of SES regardless of the method and degree of formalization. The external flows, representing the SES interaction with the environment are modeled as factors somehow influencing the internal flows. Thus, the SES environment is considered as an external resource for the SES itself. This modeling principle, based on the primacy of SES in relation to the environment, does not reflect the very essence of the existence of SES as an open system, created by the environment to fulfill the mission determined by the environment. In terms of openness, the functioning of any SES is determined precisely by the external information flows that form the state of the system [23].

The interaction of SES with the environment is a structured set of signs, texts—contracts, agreements, executive documents, i.e. a set of information about a legal entity and environment, which is constantly growing, forming a flow of information. It is natural to divide such a flow into two: the input flow is the information that represents what the SES is for the environment, and the output flow is what the environment is for the SES.

The concept of a flow is always associated with time, respectively, each state of the SES is associated with the current time of the system's life:

$$SES\_State_t = F(InputStream_t, OutputStream_t), \quad (1)$$

where SES_State_t—the system state at current time t; $InputStream_t$—input information flow (influence of the environment on the system); $OutputStream_t$—output information flow (system impact on the environment); F—way of correlating input and output information flows that form the current state of the system.

The input flow represents the resources that the environment transfers to the system for the execution of its mission (tangible and intangible objects). The output stream is formed as a transfer of the results of the system's activity, demanded by the environment (these can also be tangible and intangible objects).

SES itself is not a material object, it is an artifact created by the activities of people, providing the conditions for their existence [24]. In terms of artifacts categorizing, the SES is an informational phenomenon, since the state of any SES and any input and output flows in the SES are always identified with the flows of information.

Any change in the input and output flows over time $(t + \Delta t)$ leads to a change in the state of the system:

$$SES_{State_{t+\Delta t}} = F(InputStream_{t+\Delta t}, OutputStream_{t+\Delta t}). \quad (2)$$

The SES functioning, i.e. the execution of the SES its mission consists in creating a new input stream, leading to an acceptable system state that ensures the existence of the system itself at a time $(t + \Delta t)$, i.e.:

$$InputStream_{t+\Delta t} = \Phi(SES\_State_t, OutputStream_t), \quad (3)$$

where Φ—a way of correlating the influence of the state of the system and the output flow formed by it on the reaction of the environment in the form of the input flow.

The influence of the output flow on the formation of the input flow of the system in the classical control theory is called feedback. However, in the context of SES management, the representation of such an influence by any functional dependency is not possible due to the uncertainty of the reaction of the environment to the system.

The formation of a new output flow is carried out as a result of actions performed by the system, determined by the input flow:

$$OutputStream_{t+\Delta t} = \Psi(InputStream_t \oplus OutputStream_t), \quad (4)$$

where Ψ—a way of correlating the results of actions performed by the system and the new output flow generated by it; «$\oplus$»—pseudo-mathematical operation reflecting the way the output flow is generated.

The ways of correlation indicated in formulas (1–3) as F, Φ and Ψ, respectively, are chosen by people, and due to the non-numerical nature of the thinking process, they are not reducible to any functional dependencies. Therefore, in the general case, F, Φ and Ψ symbolize so-called "thinking" functions inherent in people.

Thus, the system of equations:

$$\begin{aligned}
SES_{State_t} &= F(InputStream_t, OutputStream_t),\\
SES_{State_{t+\Delta t}} &= F(InputStream_{t+\Delta t}, OutputStream_{t+\Delta t}),\\
InputStream_{t+\Delta t} &= \Phi\big(SES_{State_t}, OutputStream_{t+\Delta t}\big),\\
OutputStream_{t+\Delta t} &= (InputStream_t) \oplus (\Delta OutputStream).
\end{aligned} \tag{5}$$

is a pseudo-mathematical model of an open SES, reflecting the dynamics of the system's existence and the fulfillment of its mission. Any SES exists, interacting with the environment through information flows. On the other hand, the environment, interacting with the SES, provides an opportunity for self-realization.

4 Principles for Modeling Information Flows in Open Socio-Economic Systems

Thus, the authors propose the following principles for modeling information flows in open socio-economic systems:

1. Openness is a key property of any SES, which ensures its functioning in interaction with the environment.
2. The functioning of the SES is determined by external (input and output) information flows that form its state.
3. The input information flow is formed by the resources that the environment transfers to the SES for the execution of its mission, the output flow is formed as the transfer of the results of the SES activities demanded by the environment.
4. The state of the SES is determined by the "balance" of input and output information flows.
5. The dynamics of input and output information flow leads to a change in the state of the SES.
6. The input and output flows are interconnected and interdependent by the fulfillment of the SES mission, which determines the system's existence.

Any SES, as an open system created by the environment for the execution of its mission determined by the environment, can be considered as a form of interaction of the environment with itself, and proposed principles of modeling information flows reflect the dualism of the relationship between the system and the environment (as shown in Fig. 1).

5 Conclusion

The proposed principles of modeling information flow make it possible to model SES as an information fragment of the network information space. The information flows themselves are a form of the information network functioning. The network

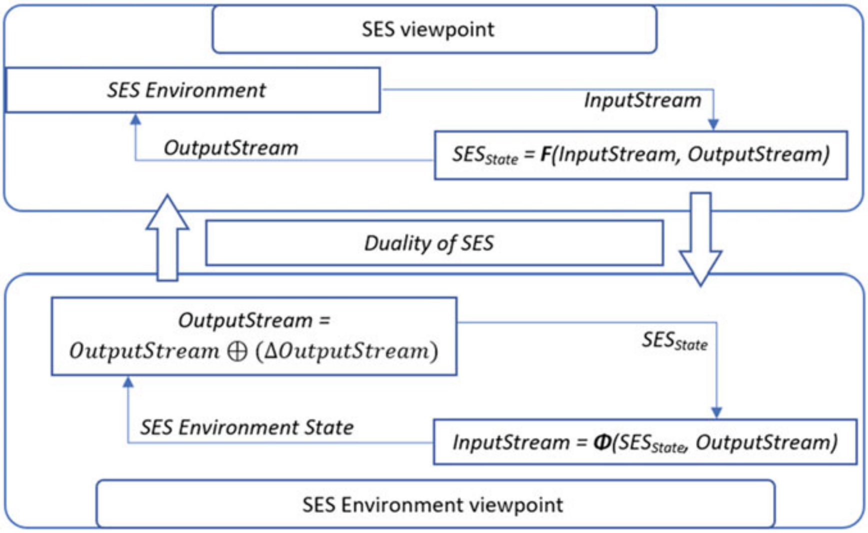

Fig. 1 Relationship between the system and the environment through information flows

controls the SES through information flows that reflect the impact of the network on the system, and identify the SES as belonging to the network.

Thus, socio-economic systems form a network of relations with each other, which ultimately determines the existence of the society itself. The functioning of each SES in the network is a process of continuous formation of the society as integrity, which disintegrates into a plurality of socio-economic systems, but again restores the global network of life as itself. At the same time, the interactions, contradictions, and even conflicts arising between information flow in the network are the sources of the "power" that allows the SES to carry out its activities called the SES mission in the network.

Modeling SES as an information fragment of the network information space justifies the possibility of digitalization of the society formed by a plurality of open interacting SES (organizations).

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Society 5.0: Intelligent Energetics

Life Cycle Control of Electric Grid Equipment Based on Historical Economic Indicators

O. M. Protalinsky, A. U. Shvedov, and Anna A. Khanova

Abstract The issue of equipment lifecycle management is considered—implementation of the program of maintenance and repair, capital replacement of equipment. During the life cycle of electrical grid equipment, it is possible to identify a period in which the total cost of repairing the equipment in the future will exceed its capital replacement with new equipment with similar indicators. The materials of domestic and foreign authors were studied on the topic of the operation of the power grid equipment park, regulatory and reference information for distribution power grid companies. Calculated functions are derived based on the economic indicators of the equipment - the cost of repairs, the book value, the level of inflation, taking into account the operation of the equipment. According to the task, a decision-making agent was developed for managing the life cycle of equipment of power grid companies based on economic indicators. The implementation of this algorithm in the production asset management system of interregional distribution grid companies will optimize the life cycle costs of a piece of equipment. The calculations made based on the decision-making algorithm in managing the life cycle of the equipment of power grid companies based on economic indicators indicate a decrease in the total cost of equipment by up to 10%. Investing the freed-up capital will allow the existing high-quality characteristics of the power grid equipment fleet.

Keywords Status index · Grid equipment · Maintenance · Repair · Replacement function · Life cycle

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1 Introduction

Interregional distribution grid companies supply electricity from generation companies to consumers. They have an impressive fleet of electric grid equipment, which can reach tens of millions of units (including supports and spans). Each equipment type has its own service life and is constantly wearing out [1]. To keep it in working condition and reduce the number of accidents, which often result in having to compensate the consumers, the technical policy of Rosseti "On the Uniform Technical Policy in the Power Grid Complex" [2], which contains the basic information on equipment maintenance and repair (M&R).

The underfunding of repair and investment programs leads to the situation when cost planning for equipment repair is made only for the short term without taking into account the efficiency of complete replacement of equipment in the conditions of increased repair cost for old equipment and increased payments for compensation of damage to consumers. Modern enterprise business asset management systems (BAMS) accumulate historical data on equipment repairs during its life cycle, the analysis of which makes it possible to establish a period in which the total cost of repairing obsolete equipment in the future will exceed the cost of replacing it with new similar equipment, along with its technical support.

Alekseev et al. [3–5], and others devoted their studies to the issues of the organizational and economic efficiency increase for the maintenance and replacement of production assets and management of equipment life cycle. Despite the extensive research base, the existing models of equipment assessment, repair, and replacement planning are based on a personalized approach (requires information about each unit which is very expensive in terms of time and financial resources) and assessment of physical and chemical, and operational factors affecting the condition of the equipment [6–10]. There are no models that take into account the interrelation of economic impacts and the residual operation life of the equipment and allow using minimum initial information to assess the integral state of the enterprise equipment and the costs necessary for its repair. The results of the analysis and modelling will allow ensuring the increase of power grid company equipment life cycle management efficiency under the condition of implementing the Industry 4.0 concept [11].

2 Analysis of Interregional Power Grid Company Electrical Grid Equipment Life Cycle Management

During the life cycle of electrical grid equipment, maintenance and restoration of its performance are carried out. Following STO 34.01-24-002-2018 current, mid-life, overhaul, unscheduled and emergency types of repair are defined.

Current repairs (CR) of equipment are performed for restoration of serviceability and partial restoration of the unit life with the replacement or restoration of components of limited nomenclature and management of the unit technical condition according to the scope provided in the documentation [12].

Mid-life scheduled repairs (MLR), as opposed to current repairs, provide for the disassembly of equipment, its individual units, the measurement of defects, and drawing up an inventory of defects. Among other things, this type of repair includes inspection of drawings, sketching, and testing of individual electrical equipment assemblies.

Equipment overhaul (OH), performed to restore the serviceability and full or close to full restoration of unit life with the replacement of restoration of any of its components, may involve full unit disassembly, repair of basic and prismatic components and assemblies, replacement or restoration of all worn components and assemblies with new and more modern ones, assembly, adjustment and testing of the unit [13, 14]. When carrying out an overhaul, the equipment must not change its functional purpose. The purpose of equipment overhaul is to restore its technical and economic characteristics to values close to the design ones. The most expensive types of repairs are overhauls and emergency repairs.

A multi-year maintenance and repair (M&R) plan is compiled for scheduled works. An annual M&R plan is created every year based on the multi-year plan. The equipment is included in the multi-year plan by the frequency of repairs for each type, taking into account the priority of the most expensive (in descending order – overhaul, mid-life, current) [15–17]. With each new repair (apart from overhauls), the condition of the equipment becomes worse compared to the design parameters, and the cost of repairs is higher [21–23]. At some point, future repairs are not profitable and a complete replacement of the equipment will be an economically feasible solution [18, 19]. Figure 1 shows the life cycle of the oil circuit breaker, with its maintenance cost, and a comparison with the option of replacing it at year 22 of operation.

Electrical grid equipment is an element of the network hierarchy along the supply chain from generation facilities to consumers. According to the methodology of the Ministry of Energy No. 123 dd. 19/02/2019 it is possible to calculate the failure consequence indicator, which is measured in monetary terms [20]. Before creating a multi-year plan, it is necessary to analyze the feasibility of the complete replacement of equipment.

3 The Procedure of Life Cycle Management of Power Grid Companies' Equipment Based on Economic Indicators

The decision-making algorithm for managing the power grid companies' equipment life cycle is based on monitoring changes in the equipment condition level depending on repair maintenance costs and allows to determine the optimal replacement period for a group of homogeneous equipment of a power grid company (Fig. 2).

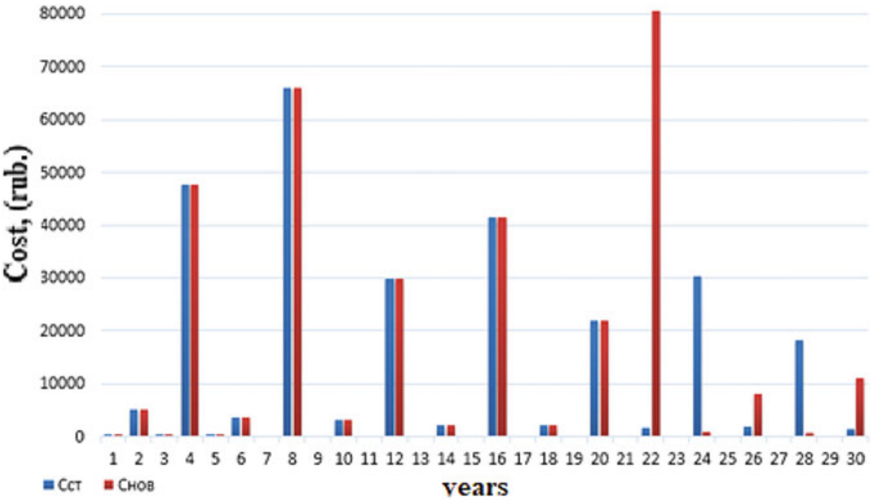

Fig. 1 Distribution of equipment repair costs over the life cycle of the oil circuit breaker VT-35-630-12,5

To prepare the equipment maintenance, forecast it is proposed to perform the following actions based on the equipment repair data for a certain brand:

1. Import historical data from external systems, including equipment repairs and failure consequence data from the BAMS and new equipment (or counterpart) cost data from the Accounting Information System (AIS).
2. Calculate the average annual cost for each type of repair (CR, MLR, OH, M&R) for a particular brand of equipment, setting the selection by equipment. for each of the periods of equipment operation, equal to the frequency of overhauls (for example, 8, 16, 24, etc. years):

$$C_{gen} = \frac{\sum_{j=1}^{t} C_{nj}}{n}, \tag{1}$$

where C_{nj} is the annual cost of maintenance of the n-th item of equipment in the j-th year, $j = \overline{1, t}$; t is the period for which the cost of equipment is recorded (number of years); n is the number of recorded pieces of equipment of a particular brand.

Calculate the cost of equipment maintenance Cold – taking into account the frequency of work for each type of repair (taking into account the priority of more time-consuming repairs) and the rated service life (for example, for oil circuit breakers 35 kW and up – CR 2 years, MLR 4 years, OH 8 years, rated service life 30 years), taking into account on each period the repair costs each period (duration and frequency of OH) C_{gen}:

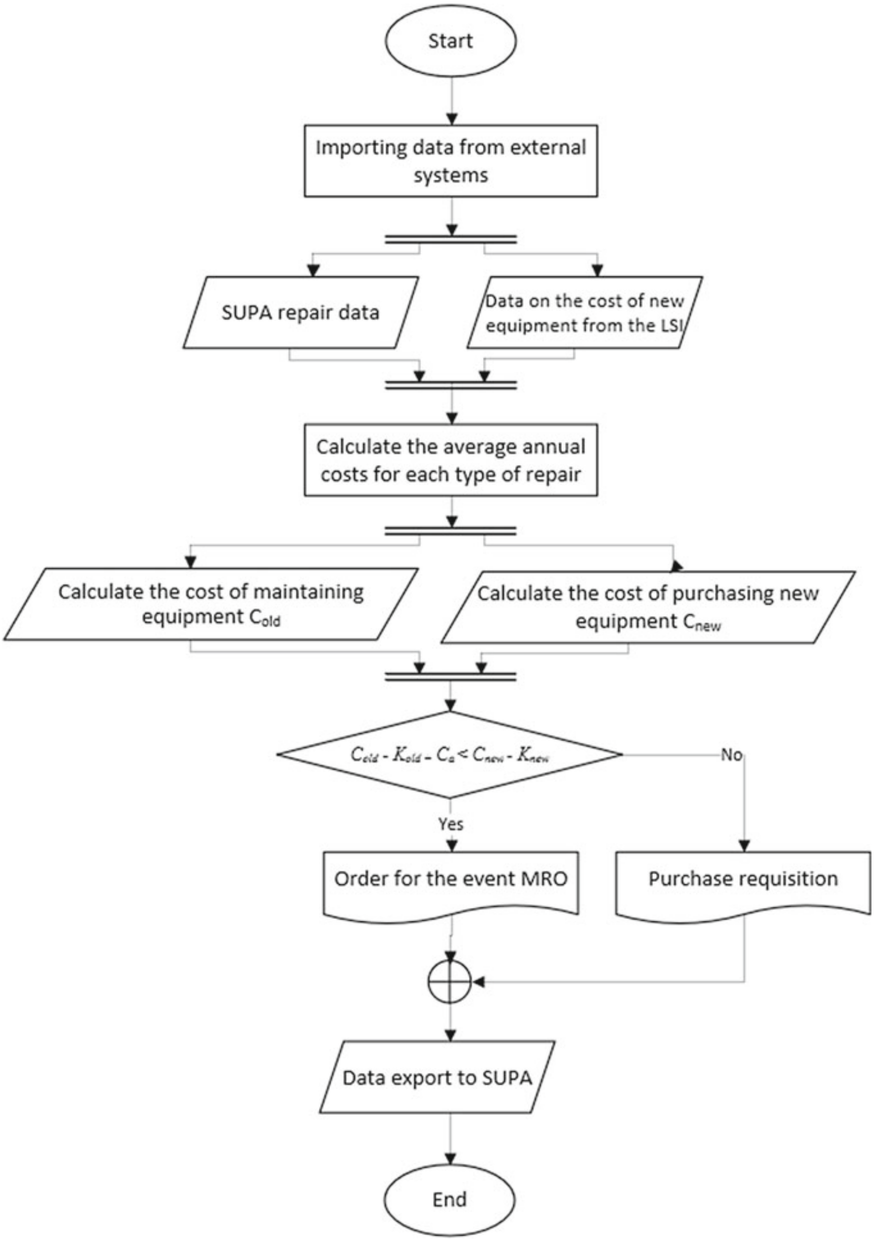

Fig. 2 The decision-making algorithm for managing the power grid companies' equipment life cycle based on economic indicators

$$C_{old} = \sum_{j=1}^{t} \left(C_{gen_j} \cdot D_j \right), \tag{2}$$

where C_{old} is the cost for the period t for the old equipment; t is the period until the end of the rated equipment service life; D_j is the discount factor in the j-th year, $j = \overline{1, t}$;

$$D_j = (1 - r)^j, \tag{3}$$

where r is the estimated rate; j is the year number, $j = \overline{1, t}$. The estimated rate is calculated using the Fisher equation:

$$r = r_0 + i + r_0 \cdot i, \tag{4}$$

where r_0 is the current key interest rate of the Central Bank of the Russian Federation; i is the projected inflation rate.

1. Calculate the costs of buying new equipment C_{new}, taking into account the cost of new equipment and its scheduled maintenance:

$$C_{new} = K_{new} + \sum_{j=1}^{t} \left(C_{plj} \cdot D_j \right), \tag{5}$$

where K_{new} is the investment into new equipment, C_{pl} is the scheduled repairs:

$$C_{pl} = \sum_{j=1}^{t} (\text{С}_{\text{об}_j} \cdot D_j), \tag{6}$$

where C_{pl} is the planned maintenance costs of equipment for the period t (from the commissioning of new equipment and the end of the standard life of the replaced equipment).

It is proposed to calculate the costs of support of the old and installation of new equipment annually when drawing up a multi-year M&R program so that the equipment can be excluded from it in the purchase acts or investment programs. A sign of exclusion from the repair program of the equipment is the following ratio:

$$(C_{old} - K_{old +} C_a) < (C_{new -} K_{new}), \tag{7}$$

where K_{old} is the residual book value of old equipment; K_{new} is the residual book value of new equipment, C_a is the cost of emergency repairs, C_a is the cost of emergency repairs:

$$C_a = (C_t + IN) \cdot u, \tag{8}$$

C_t is the costs of 1 repair, *IN* is the consumer compensation, *u* is the equipment unit failure rate;

2. Compare the cost of maintaining and repairing the old equipment C_{old} with the cost of buying new equipment C_{new} and maintaining it, taking into account the residual book value.
3. As a result, the creation of an M&R Order or a Purchase Order Request document is recommended.
4. Export data to BAMS.

4 Example of Synthesizing the Parameters of a PID Controller Model

Let us examine the described algorithm using the repair data imported from BAMS and the new equipment cost data imported from AIS. For example, the equipment is 22 years old and the issue of its replacement is on the agenda (Table 1). According to the data presented, one can see that equipment replacement including maintenance (251,670.63 rubles) is cheaper than its maintenance (279,805.24 rubles), taking into account the residual book value of the equipment Knew and the discount factor Dj. The profit amounts to (28,134.61 rub.).

5 Conclusion

The developed methodology, based on economic historical indicators, which have been maintained in AIS for more than 10 years, will optimize the life cycle costs of some equipment, free up funds for unscheduled work and investment in new equipment, which in turn will affect the fault tolerance of the entire fleet of equipment and reduce the electricity consumer compensation costs.

Table 1 Calculation of the equipment maintenance and replacement costs

Year of operation	Repair type	MRO without maintenance, rub	MRO with maintenance, rub	Replacement of equipment for 22 years without maintenance, rub	Replacement of equipment at year 22 with maintenance, rub	Discount factor (D)	C_{old}	C_{new}
1		0	495	0	495	1.00	495.00	495.00
2	CR	5059	5554	5059	5554	0.92	5122.67	5122.67
3		0	495	0	495	0.85	421.10	421.10
4	MR	60,184	60,679	60,184	60,679	0.78	47,611.32	47,611.32
5		0	495	0	495	0.72	358.23	358.23
6	CR	5059	5554	5059	5554	0.67	3707.31	3707.31
7		0	495	0	495	0.62	304.75	304.75
8	OR	115,625	116,120	115,625	116,120	0.57	65,938.83	65,938.83
…	…	…	…	…	…	…	…	…
21		0	495	0	495	0.20	98.27	98.27
22	CR	8499	8994	440,000	440,495	0.18	1646.88	80,657.27
23		0	495	0	495	0.17	83.60	83.60
24	OR	194,250	194,745	115,625	116,120	0.16	30,335.42	18,088.01
25		0	495	0	495	0.14	71.12	71.12
26	CR	13,599	14,094	5059	5554	0.13	1867.61	735.99
27		0	495	0	495	0.12	60.50	60.50
28	MR	161,775	162,270	60,184	60,679	0.11	18,292.93	6840.45

(continued)

Table 1 (continued)

Year of operation	Repair type	MRO without maintenance, rub	MRO with maintenance, rub	Replacement of equipment for 22 years without maintenance, rub	Replacement of equipment at year 22 with maintenance, rub	Discount factor (D)	C_{old}	C_{new}
29		0	495	0	495	0.10	51.47	51.47
30	CR	13,599	14,094	5059	5554	0.10	1351.60	532.64
31		0	495	0	495	0.09	43.78	43.78
32	OR	310,800	311,295	115,625	116,120	0.08	25,396.90	9473.61
Total equipment maintenance							279,805.24	310,819.30
Residual book value (K_{old})							0.00	59,148.67
Total with K_{old}							279,805.24	251,670.63

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Structural Analysis of the Pricing for the Power Grid Company Team Management Process Based on the System Dynamics Model

A. R. Kinzhalieva and Anna A. Khanova

Abstract The lack of the necessary investment in the electric grid complex over the past 20 years has led to a significant physical and technological obsolescence of electrical networks. In this regard, the task is automatic. The task of ensuring the reliability of the provision of services by electric network companies with a minimum level of costs largely depends on the reduction of the duration of the power interruption of consumers, which can be achieved by improving the process of managing on-duty personnel of operational and field teams. The task of improving the process of managing the field service teams of a power grid company in case of accidents and technological failures is considered. A conceptual description of a system dynamic model based on the Forrester flow diagram is given. A formal description of the process of own and borrowed resources operation pricing is presented. An applied basic system dynamics model for creating simulation models of electricity distribution companies is developed and proposed.

Keywords Simulation modeling · System dynamics · Costs · Power grid company · Field service teams · Accident

1 Introduction

Modern society increasingly depends on a reliable power supply to ensure a sufficient level of functionality and degree of basic need satisfaction. As a consequence, an uninterrupted electricity supply is critical to society, and power grid companies are becoming one of society's most important infrastructures [1] defined as the physical and logical systems necessary for social welfare [2]. Achievement of this task is assessed by the service reliability level [3]. This indicator is directly affected by the average duration of consumer power supply interruption [4]. Therefore, finding ways

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to reduce the duration of power outages is required [5]. Particular attention should be paid to the issue of the organization of the team management process during accidents and technological failures, the quality of which depends on the timing of accident and technological failure corrective measures implementation, which ultimately affects the overall customer satisfaction [6]. On the other hand, the rational use of resources allows optimizing the costs associated with their use [7].

The process of managing field service teams during the occurrence of accidents and technological failures in electricity distribution companies is complex, with a large number of possible situations and states. The works of Russian and foreign authors concerning the management and optimization of repair work processes describe the application of artificial intelligence methods [8, 9], including neural networks [10, 11], fuzzy set theory [12, 13], and simulation modeling [14–16]. At the same time, the stochastic nature of emergencies, which is influenced by the specific features of the work of field service teams, the distribution of material and technical resources and the pricing implies the advisability of choosing the simulation modeling method as a research tool [17]. Among the known methods of building simulation models (discrete-event, agent-based, or system-dynamic) it is necessary to choose an approach to modeling, the end result of which should not be the prediction or anticipation of future economic situations, but understanding the essence of the dynamics of the system under study [18, 19]. It is the simulation models of system dynamics that will make it possible to bypass a number of limitations in the study of the management process for field service teams caused by the practical impossibility of obtaining information about this process in various situations during which the system and environment parameters change over time and a number of management processes can be described only approximately [20, 21].

The purpose of this work is to improve the efficiency of the pricing process in the field service team (FST) management for electricity distribution companies by creating and analyzing the behavior of the system dynamics model.

2 Materials and Methods for Solving The Problem of Process Cost Management

In case of receiving an accident alert, the network control center (NCC) determines the category of accident complexity, then determines the adequacy of its own resources (OR)—the number of on-duty personnel and equipment at the FST locations. To eliminate an accident, the NCC forms the FST and provides it with the equipment, depending on the complexity category and the estimated time of elimination. In the event of the lack of own resources, the entire available FST reserve, as well as involved resources (IR)—contractor personnel and equipment, are directed to the accident location. In this case, the FST is formed from ORs and IRs. In the case where all own resources are involved in the emergency and recovery work, the minimum required contractor team is involved. In the simulated system, accidents occur according to the Poisson flow with a given intensity for m days of model time. Suppose the field service teams composed of a total of A people are on duty 24 h a day. The total number of equipment that can be involved is B units. The model implements a mechanism for equipping the FST with personnel and rented equipment in case of lack of own resources, while at the same time a pricing process is implemented.

We begin the construction of the system dynamics model by creating a conceptual description of the system in the form of a Forrester flow diagram [22]. The diagram (Fig. 1) shows the two main cost flows generated by the operation of OR and IR. These flows are similar to each other and are broken down into cost flows related to labor compensation and equipment operation. According to the communicating vessels principle, the costs accumulated at previous levels affect the cost value at subsequent levels (in the diagram, the levels are represented as rectangular blocks 1–9). The cost value at the initial level of each flow depends on the rate of cost flow (in the diagram, the rates are represented as valves I–V). The rate of cost flows is directly affected by: the number of resources involved (personnel and equipment) (A, a_i, a_j, b_i, b_j), tariff rates $(S_1, S_2, S_3, S_4, S_5)$. In this case, the variable A is presented as a constant, because the constant part of the on-duty personnel labor compensation is made regardless of whether the personnel was involved in the accident elimination. This model reflects a simplified scheme for calculating the labor compensation costs of own and involved personnel and costs associated with the operation and rental of equipment.

The following equations determine the cost levels of resource operation.

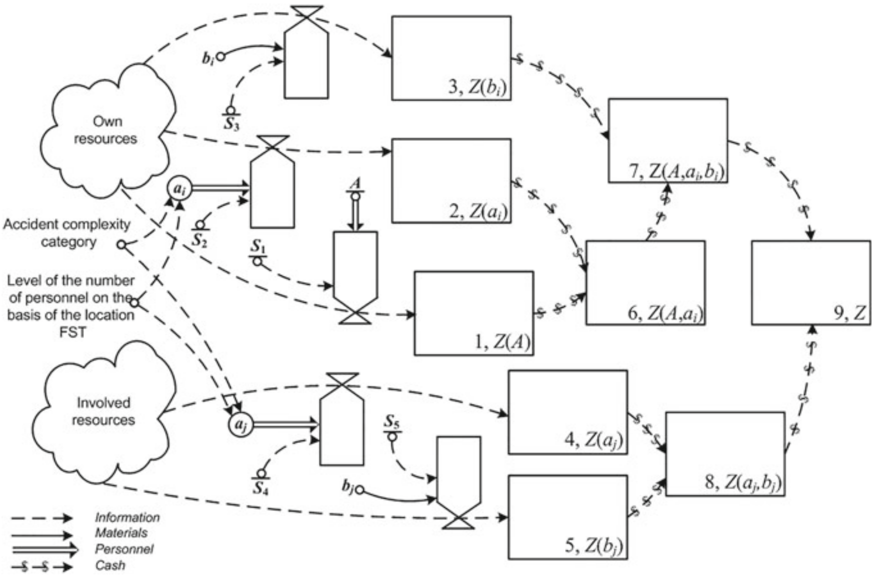

Fig. 1 Diagram of the cost flows associated with the elimination of accidents

The cost value of own personnel (constant part) *Z(A)* is calculated using the following formula (Fig. 1, level 1):

$$Z(A) = A \times S_1 \times m \tag{1}$$

where S_1 is the size of the constant part (tariff rate) of own personnel salary, Rub.

The amount of labor compensation costs for own personnel (variable part) $Z(a_i)$ is calculated using the following formula (Fig. 1, level 2):

$$Z(a_i) = \sum_{i=1}^{k} T_i \times a_i \times S_2 \tag{2}$$

where k is the number of accidents that occurred over m days of the model time eliminated using own resources; S_2 is the rate accrued by own personnel a_i, involved at the time T_i to eliminate the i accident, Rub., $i = \overline{1, k}$.

The cost value of operating own equipment $Z(b_i)$ is calculated using the following formula (Fig. 1, level 3):

$$Z(b_i) = \sum_{i=1}^{k} T_i \times b_i \times S_3 \tag{3}$$

where S_3 is the rate for 1 machine-hour (model time) of work of own equipment b_i involved at the time T_i to eliminate the i accident, Rub.

The labor compensation cost value for the contractor's personnel $Z(a_j)$ is calculated using the following formula (Fig. 1, level 4):

$$Z\left(a_j\right) = \sum_{j=1}^{l} T_j \times a_j \times S_4 \tag{4}$$

where l is the number of accidents occurring over m days of the model time, for the elimination of which the contractor is involved; S_4 is the rate accrued by the contractor's personnel a_j involved at the time T_j to eliminate the j accident, Rub., $j = \overline{1, l}$.

The value of the cost of operating rented equipment $Z(b_j)$ is calculated using the following formula (Fig. 1, level 5):

$$Z\left(b_j\right) = \sum_{j=1}^{l} T_j \times b_j \times S_5 \tag{5}$$

where S_5 is the rate per 1 machine-hour (model time) of the rented equipment b_j involved at the time T_j to eliminate the j accident, Rub.

The cumulative labor compensation cost amount for own personnel $Z(A,a_i,)$ is calculated using the following formula (Fig. 1, level 6):

$$Z(A, a_i) = Z(A) + Z(a_i) \tag{6}$$

The cumulative value of the labor costs of own personnel and operation of own equipment $Z(A,a_i,b_i)$ is calculated by the following formula (Fig. 1, level 7):

$$Z(A, a_i, b_i) = Z(A, a_i) + Z(b_i) \tag{7}$$

The cumulative labor compensation cost value of the contractor and the operation of rented equipment $Z(a_j,b_j)$ is calculated using the following formula (Fig. 1, level 8):

$$Z\left(a_j, b_j\right) = Z\left(a_j\right) + Z\left(b_j\right) \tag{8}$$

The total cost value Z is calculated using the following formula (Fig. 1, level 9):

$$Z = Z(A, a_i, b_i) + Z\left(a_j, b_j\right) \tag{9}$$

The cost flow diagram (Fig. 1) is designed to structure the costs of own personnel and contractor personnel, as well as the amount of costs associated with the operation and rental of the equipment and is implemented in the AnyLogic simulation software (Fig. 2).

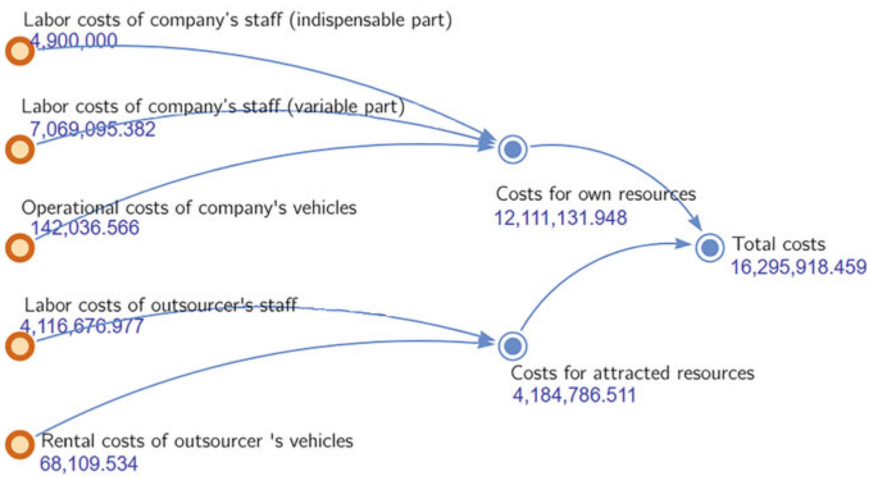

Fig. 2 System dynamics model diagram in Anylogic

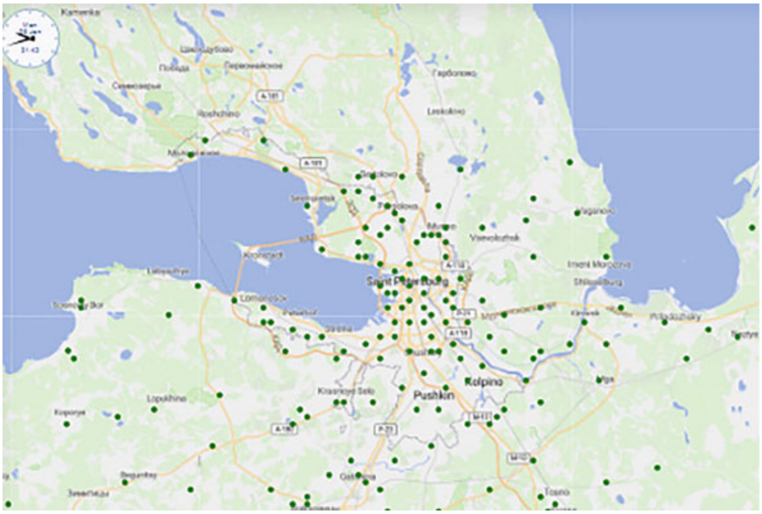

Fig. 3 GIS map of the system dynamics model in Anylogic

The animation diagram of the model should display a GIS map, on which power facilities are marked with green GIS points. Their color should change depending on the difficulty category of the accident: red if there is a category 1 accident; orange if there is a category 2 accident; yellow if there is a category 3 accident. During the entire time of accident elimination, the text information near the GIS point containing the number of involved own personnel and equipment and, separately, the number of involved personnel and rented equipment should be displayed [23]. At the end of the accident elimination time, the GIS point changes color to green, and the text information disappears (Fig. 3).

Depending on what system information is needed and what task is required to be solved using the simulation model, the planning of the experiment is performed taking into account resource constraints. Machine experiment planning is essentially a plan for obtaining the necessary amount of information, the cost of which can vary depending on the method of data collection and processing. Computer simulation experiments are expensive in terms of experimenter time and labor, as well as machine time. The more effort an experimenter puts into one study, the less time they can spend on another, so it is important that they plan the experimentation to get as much information out of each experiment as possible. Thus, the main goal of planning experiments is to determine the most important factors in order to conduct the least number of runs in the model experimenting process.

3 Experimental Results of the System Dynamics Simulation Model

The decomposition of the experiment planning process with the simulation model of cost analysis for the field service team management process of the power grid company is presented in the EPC notation (Fig. 4).

It is assumed that the work with the simulation model will be performed by the Analytical Competence Center (ACC) by a user group with the ACC Specialist role.

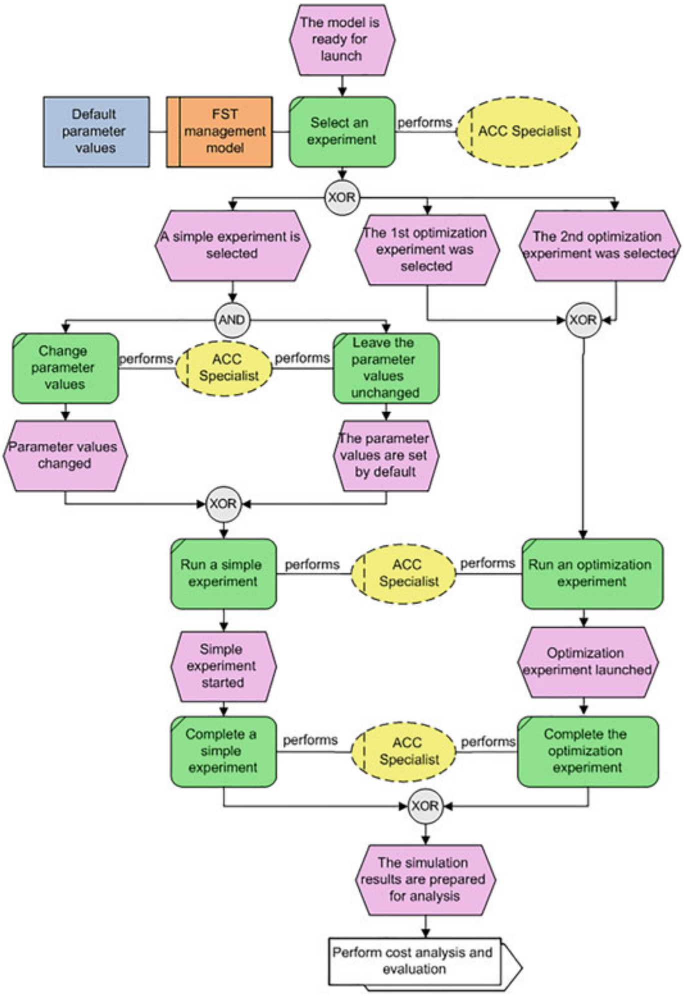

Fig. 4 Stages of the experiment with the model in EPC notation

The simulation model allows an ACC Specialist user to change the default parameter values before running the model. It is assumed that AnyLogic Private Cloud is installed inside the corporate network of a power grid company and PC users connected to the corporate network (with no limit on the number of users) will be able to view the model uploaded to AnyLogic Private Cloud by an ACC Specialist user.

The costs associated with the use of resources to eliminate accidents are visually accumulated in the running model window throughout the simple experiment. The diagrams (Fig. 5) are designed to display the time trend of the cost values for own personnel labor compensation $Z(A,a_i)$; operation of own equipment $Z(b_i)$; contractor labor compensation $Z(a_j)$; operation of rented equipment $Z(b_j)$.

The Consumer power outage duration chart (Fig. 6a) is designed to display the

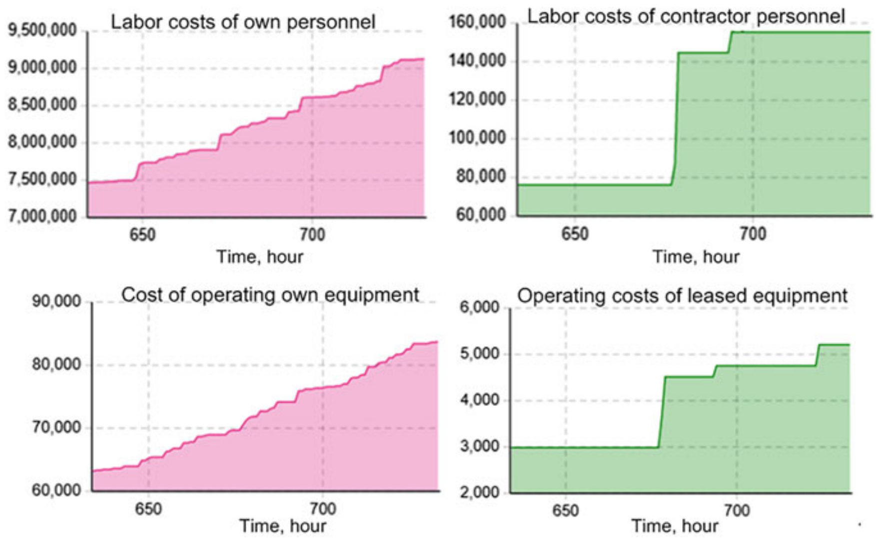

Fig. 5 Time trends of cost values (animation fragment)

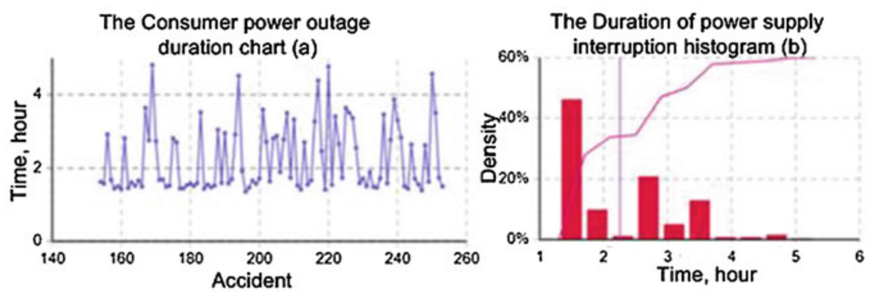

Fig. 6 Time trends of power outage duration (animation fragment)

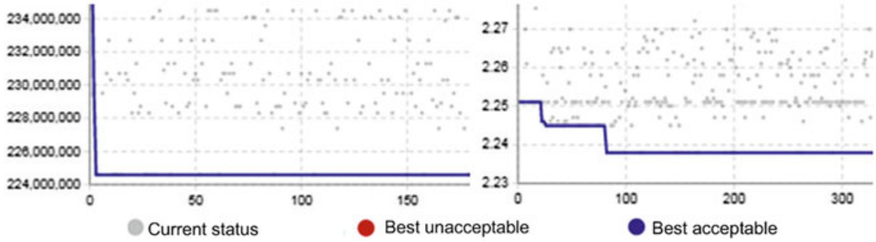

Fig. 7 Experiments with the model

time trend of the average consumer power outage duration. The Duration of power supply interruption histogram (Fig. 6b) is designed to display data on the duration of consumer power supply interruption: the histogram divides the time scale into 10 intervals; the interval in which a greater number of durations occur becomes higher, which means a greater density of entries in this interval.

In determining the optimal number of on-duty personnel and the optimal number of equipment to minimize costs (optimization experiment 1), the best result $Z =$ 224,609,199.40 Rub. was found, which is achieved when $A = 75$ and $B = 37$ (Fig. 7a). In determining the optimal number of on-duty personnel and the optimal number of equipment to reduce the duration of power supply interruption (optimization experiment 2), the best result (power outage duration equal to 2.238 h) was found, which is achieved with $A = 111$ and $B = 50$ (Fig. 7b).

The system dynamics simulation model was developed for Lenenergo PJSC and is a basic model for creating models of similar electricity distribution companies. To adapt the system to the conditions of other power grid companies, it is possible to add and/or change significant factors affecting the level of abstraction, customize the algorithm of field service team formation, set the locations of power facilities on the GIS map, etc.

4 Conclusion

In order to improve the efficiency of field service team management in case of accidents and technological failures, a simulation model with elements of system dynamics was developed to determine the optimal number of resources involved in eliminating accidents and technological failures, in which the average duration of consumer power supply interruption is minimal, as well as to optimize costs associated with personnel compensation and the operation and rental of equipment involved in the elimination of accidents and technological failures.

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Calculation Models of Energy Consumption and Methods of Their Analysis in Decision Support Systems for Industrial Enterprises

Nadezhda Serdyukova, Tatiana Shulga, Alexander Sytnik, and Svetlana Kumova

Abstract The chapter is devoted to the problem of reducing the costs of industrial enterprises by choosing the most profitable model for settlements with the electricity supplier. The calculation model is the rules for determining the cost of electricity, corresponding to a specific set of technical and economic conditions for power supply and characteristics of metering objects. The calculation model of energy consumption for enterprises is a variable value and depends primarily on the changing schedule of energy consumption of the enterprise which in turn depends on the volumes and types of products. The chapter describes the decision support system (DSS) which helps to reduce the cost of electricity and the corresponding methodology for choosing a calculation model of electricity consumption, including methods of statistical and data mining. The models and algorithms for processing data on various technical and economic indicators of energy consumption are implemented in DSS support the accounting for the dynamics of changes in the electricity and power market, as well as the ability to build arbitrary calculation models with the required consumer characteristics and calculation rules. The implementation of the DSS at two industrial enterprises showed that the savings from the choice of the calculation model amounted to 13 and 15% per year.

Keywords Energy consumption · Calculation model · Technical and economic indicators · Cluster analysis · Decision support system · Reduction of energy costs

1 Introduction

In the context of Russia's transition from a planned to a market economy, opportunities are being realized for more active consumer behavior in managing reduced costs for their energy consumption (EC), including by choosing the most profitable model for settlements with an electricity supplier.

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The calculation model refers to the rules for determining the cost of electricity, corresponding to a specific set of technical and economic conditions of power supply and metering objects characteristics.

The construction of calculation models for a specific consumer of electricity and the calculation on their basis of the cost of electricity consumed is a laborious and costly task, requiring in the general case to attract a large number of highly qualified specialists such as economists with specializations in the field of power supply, engineers and programmers which requires significant costs and eliminates the effect of energy-saving. It should also be noted that the calculation model of energy consumption is a variable value and depends, inter alia, on the changing schedule of energy consumption of the enterprise, which depends on the volumes and types of products. Therefore, today consumers are forced to use the calculation model proposed by the supplier. The solution to this problem seems to be the introduction at enterprises of a DSS with the functions of constructing possible calculation models and choosing among them the most profitable for the enterprise. This chapter briefly describes the methodology proposed by the authors for solving these problems and the structure of such a DSS.

2 Formulation of the Problem

The calculation of the cost of electricity consumed for each electricity metering object depends on a large number of calculations and accounting indicators that are interconnected by certain functions. The parameters are data sets on prices C and energy consumption volumes V which in turn depend on the set of characteristic values corresponding to this object that determine technical and economic conditions for electricity consumption.

$$f_V : X_V \to V$$

$$f_C : X_C \to C \tag{1}$$

$$f_S : X_S \to S$$

The type of functions fv, fc, fs in formulas (1), as well as the parameters in them (XV, XC, V, C) depend on the set of characteristic values corresponding to this object that determine the technical and economic conditions of power consumption.

Figure 1 shows a set of R characteristics of energy consumption accounting objects that define different calculation models. A set of sets of characteristics with their values, together with their corresponding rules for calculating electricity, forms a set of calculated models of electricity consumption. Among the given set R can identify a set of characteristics that define the algorithms for calculating the power RF, as well as many characteristics of the RX determining values of arguments in functions

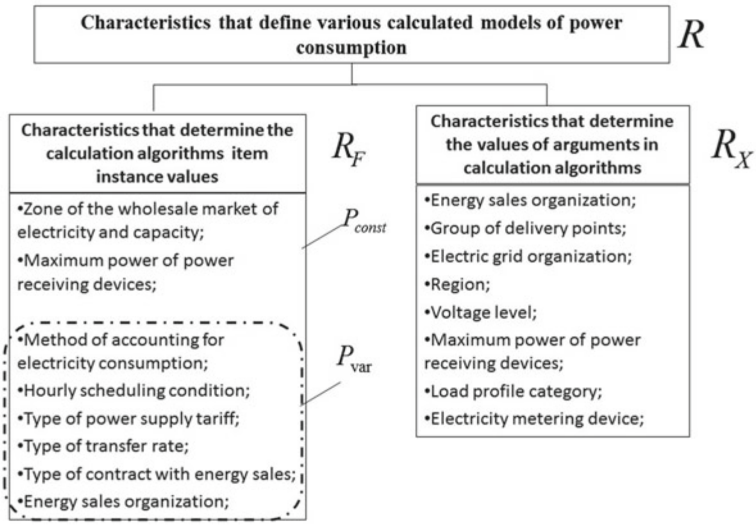

Fig. 1 Classification of characteristics defining various EC calculation models

for calculating the energy consumption. In the RF set, it can be also distinguished a set of constant signs for a given electricity consumer Pconst, and a set of variable signs Pvar. For example, a variable characteristic such as the way to account for energy consumption can take the following values: by the hour, in general for the period, by zones of the day of the billing period. It is using the values of variable characteristics that can be determined the best for the consumer calculation model of energy consumption Yo, corresponding to the minimum costs, by conducting appropriate cost calculations for different sets of characteristics that determine a particular calculation model in the aggregate.

Thus, for each electricity consumer, we can distinguish a finite set of characteristic values Ys that define different calculation models of energy consumption of which the only one set Yo determines the calculation model that is most economical for a given consumer.

The task of choosing a calculation model for industrial consumers, taking into account the specifics of the rules for forming the final cost of electricity consumed in Russia, includes the following stages:

1. Construction of calculation models corresponding to various variants of technical and economic conditions of power consumption;
2. Processing data on technical and economic indicators of power consumption for all possible variants of calculation models;
3. Analysis of data processing results on technical and economic indicators of power consumption and selection of the calculation model.

To ensure the first two stages of solving the problem of choosing a calculated model of power consumption, a data model and algorithms for processing information about the values of power consumption were proposed, which differ from the known ones in the ability to account for the dynamics of changes in the electricity market and capacity, and allow building calculation models with the required characteristics of the consumer [1].

This chapter is devoted to solving the problems of the third stage and developing a DSS that provides the implementation of all three stages of the problem of choosing a computational model for industrial consumers.

3 Research Overview

It should be noted that the characteristics that determine the various calculation models of electricity consumption and the corresponding rules for calculating the cost of electricity consumed are determined by the rules for forming the tariff practice for electricity and the final cost of electricity consumed in a particular country. Moreover, in most countries, unlike in Russia, the proposed set of tariff groups does not compare the same variety of corresponding algorithms for calculating the cost of electricity consumed, which can affect the calculation result. Therefore, in foreign studies, we are not talking about choosing a calculation model, but about choosing a tariff or tariff group that corresponds to the lowest energy costs.

In general, it is noted that one of the factors influencing the choice of a particular tariff group in Europe is the amount of electricity consumed. The corresponding tariff optimization tools are usually offered by the energy supply organizations themselves, which are not interested in raising tariffs, but, on the contrary, seek to give consumers favorable conditions for them, which results from the lack of a monopoly on the supply of energy resources in these countries. For example, in Germany, a special website Wechselpilot can be used as a tool for optimizing the electricity tariff, which compares different tariffs and offers where money can be saved. A more detailed analysis of variable electricity tariffs in Germany is presented in the article by Elisabeth Dütschke, Michael Unterländer, Martin Wietschel [2].

The article by Michal Czosnyka, Bogumila Wnukowska [3] is devoted to the problems of choosing and optimizing electricity tariffs at industrial enterprises in Poland. The Portuguese authors present a Decision Support System designed to determine the optimal tariffs for energy sales companies and electricity consumers in energy supply contracts using decision trees [4]. The research [5] develops a model based on linear programming methods for optimizing electricity tariffs to maximize the benefits of consumers by switching to a more favorable tariff. In some scientific researches [6] a nonlinear optimization model of electricity market dynamics is proposed, which can be used to obtain tariff recommendations. The model is available in two versions: a stochastic version designed for household electricity consumption, and a deterministic version suitable for large electricity consumers (for example, public buildings, industrial consumers).

Based on the dependence of the electricity tariff from the electricity consumption several studies deal with the classification of consumers based on their electrical behavior (energy consumption profiles) for the development of specific pricing strategy and tariff options, in which tariff rates take into account the consumption patterns of different types of consumers. For example, the article "User-Aware Electricity Price Optimization for the Competitive Market" [7] describes data mining methods that are used to extract knowledge related to electricity consumption patterns. A hierarchical clustering algorithm is used to generate different classes of clients. We also study [8] tools for the automatic classification of electric energy consumers by combining their characteristics. To form different classes of consumers, a comparative analysis of the performance of self-organizing Kohonen maps and the K-means clustering algorithm is presented.

Researchers provide a brief overview of data mining methods for identifying typical load profiles in electrical systems and classifying new consumers [9]. The contribution of data mining to improving payments between suppliers and consumers is also evaluated [10]. Many scientific papers have also been devoted to the use of clustering methods for classifying consumers to extract useful knowledge about electrical behavior [11–22].

Summing up the review of the available works, we can conclude that the methods for choosing the optimal electricity tariffs used in the above foreign studies are not quite suitable for Russian industrial consumers, since in Russia there are completely different rules for forming the tariff policy for electricity and the final cost of electricity consumed. In other words, the cluster analysis used by most authors cannot be used in the same way to determine the most profitable tariff group and calculation model for Russian consumers corresponding to the electricity consumption profile, since in Russia the electricity consumption profile does not play the same role when choosing electricity tariffs. In the conditions of the modern electricity and capacity market in Russia, the consumer is primarily faced with the task of conducting comparative calculations for various variants of technical and economic conditions of power consumption that correspond to the calculation models, price categories, and tariff groups defined in the legislation. However, the above approaches to classifying consumers by their electrical behavior were used in this study in a modified form by applying cluster analysis when choosing a calculated model of power consumption in addition to statistical methods for processing the results of calculations.

Moreover, at the moment there are also shortcomings in the models themselves for calculating power consumption values presented in various Russian information processing systems. For example, these models are either outdated and do not comply with current Russian legislation in the electric power industry, or they do not allow taking into account the dynamics of changes in the electricity and capacity market and calculation algorithms used by independent energy marketing organizations (NEOS) that are not taken into account in the legislation. These shortcomings also concern one of the most relevant models [1], in the development of which the authors were directly involved.

The relevance and necessity of research in this direction determined the purpose of the study, which is to develop new ways to build computational models of power consumption, taking into account the dynamics of changes in the electricity market and capacity, as well as methods for their analysis, which allows reducing energy costs and focused on improving the efficiency of power consumption management of industrial enterprises.

4 Methods for Choosing the Calculation Model of Energy Consumption

To analyze the results of processing technical and economic indicators of energy consumption corresponding to different calculation models, a methodology for choosing a calculation model of energy consumption is proposed which includes statistical methods of decision theory.

To use statistical methods, the results of processing data on technical and economic indicators for various calculation models with their corresponding sets of values of the characteristics of an energy metering object should be presented using a cost matrix (Table 1), the data in the rows of which represent a set of calculation results for each of possible sets for the consumer. The data on the columns correspond to different situations (the cost of energy in different periods of calculation). Thus, each element S_{ij} represents the value of the calculated cost of electricity consumed, corresponding to the calculation model Y_i and the calculation period m_j. The calculation period refers to the period (month) for which the electricity supplier calculates the cost of electricity consumption.

Per the proposed methodology, the minimum value for each billing period is determined $S_j^{\min} = \min_j \{S_{ij}\}$.

In the matrix B, the values of the elements b_{ij} in the j-th column are taken to be 1 if the value in this column corresponds to a certain minimum value in this column for the matrix S. And in matrix B the values of the elements b_{ij} in the j-th column are taken to be 0 if the value is different from the minimum value.

Table 1 Cost matrix of EC calculated model

EC calculation model	Periods of calculation					
	m_1	m_2	…	m_j	…	m_m
Y_1	S_{11}	S_{12}	…	S_{1j}	…	S_{1m}
…	…	…	…	…	…	…
Y_i	S_{i1}	S_{i2}	…	S_{ij}	…	S_{im}
…	…	…	…	…	…	…
Y_n	S_{n1}	S_{n2}	…	S_{nj}	…	S_{nm}

Further, the elements are summarized line by line. In this way, the number of cost occurrences with a minimum value for each set of characteristic values is determined (in the column). Then the maximum value is selected.

Thus, the selection function for this method can be written as:

$$Y = \max_i \left(\sum_j b_{ij} \right), \text{ where } b_{ij} = \begin{cases} 1 \text{ if } S_{ij} = \min_j \{S_{ij}\} \\ 0 \text{ if } S_{ij} \neq \min_j \{S_{ij}\} \end{cases}$$

In general, when using the proposed method of statistical data processing, it is recommended to use the well-known statistical methods of decision theory to compare the results obtained by choosing a calculation model of energy consumption.

To verify the application of statistical methods of decision theory when choosing a calculation model of energy consumption, the cost of energy consumed was calculated using various sets of characteristics. These characteristics are actual data on energy consumption for two industrial consumers (Mineral Fillers Plant and Greenhouses "Volga" in Balakovo) and data on prices for the period from January to December 2019.

The cost was calculated using the developed models and algorithms for processing data on energy consumption. It was found that the results of using the proposed method for choosing a calculation model of power consumption coincide with the solutions obtained using the Laplace, Wald, Savage, Hurwitz criteria and the optimal optimism method. Namely, the economic effect of changing the calculation model is to save energy costs by 10–13% and 14–15%, respectively, for each of the enterprises (depending on the method).

But since the proposed method for choosing the calculation model of power consumption turned out to be the most convenient for obtaining information about the results of calculations to the developed relational data structure, it was it that was used as a statistical method in the developed DSS.

According to the proposed methodology, at the initial assessment, it is recommended to use statistical methods of decision theory to decide on choosing a calculation model. In the future, it can be made a calculation for the past period to track the current situation and a decision to change the contractual terms of power supply.

Following Russian legislation, variants of contractual terms (calculation models) for the consumer are determined by one of its characteristics (Fig. 1) as the maximum power of power receiving devices. Namely, for consumers with a maximum capacity of at least 670 kW, it is possible to choose calculation models only with the condition of hourly accounting (in Russian legislation, they correspond to 3–6 price categories). However, it is possible that for a consumer belonging to this group, the price category corresponding to the accounting of the volume of electricity consumption as a whole for the period, may turn out to be more profitable. Therefore, at this stage of determining the possible options for calculation models, the consumer needs to consider the question of the compliance of his enterprise with a group with a maximum power of at least 670 kW. This fact of discrepancy takes place at present since the maximum capacity of the power receiving devices for many enterprises was determined 20–40 years ago when they were launched. Accordingly, if the test results are positive for a consumer with a maximum power of more than 670 kW, the number of calculated models will increase, which will require comparative calculations to select the most economical version of the contract terms.

For a consumer without hourly metering devices, first of all, the possibility of switching to calculation models with hourly accounting (3–6 price categories) is assessed. As noted above, the opposite is also possible, if the transition from a model with hourly accounting to contractual conditions involves accounting for volumes as a whole for the period (the first price category) or by zones of the day (the second price category).

For a consumer with hourly metering devices, the possibility of switching to calculation models with hourly planning is assessed (in Russian legislation, they correspond to the fifth and sixth price categories). At the same time, it is necessary to assess how accurately it is possible to predict the volume of electricity supply because the receipt of an economic effect depends on this when switching to a calculation model with hourly planning.

As an initial version of the planned volumes, it is possible to use the actual volumes of energy consumption. In this case, the deviations will be minimal (equal to zero) and in the case of a significant superiority of such a variant of the contractual conditions, it is, of course, possible to solve the problem of forming the planned volumes based on the available retrospective data on EC and assessing the effectiveness of the forecast being performed. If even in the case of minimal deviations, the economic effect turns out to be insignificant, then the problem of high-quality planning may require costs that exceed the possible economic effect from the transition to the calculation model, which corresponds to the condition of hourly planning.

If even in the case of minimal deviations, the economic effect turns out to be insignificant, then the problem of high-quality planning may require costs that exceed the possible economic effect from the transition to the calculation model, which corresponds to the condition of hourly planning.

A large number of works by various authors are devoted to the problem of predicting power consumption.

When predicting the volume of electronic production of an industrial enterprise, many different factors are distinguished, among which one of the main ones is the volume and types of products. When developing DSS for the possibility of monthly planning of hourly power consumption, the approach described in several articles [23] was used. By this approach, using cluster analysis, the classification of daily load schedules and technological states of production is carried out, based on which a forecast model is built, which makes it possible to predict hourly power consumption for a month using the planned daily and monthly volumes of production with satisfactory accuracy.

Also, when assessing the economic effect obtained by switching to calculation models, which correspond to the hourly metering condition (in Russian legislation, they correspond to 3–6 price categories), it is important to consider the possibility of reducing the value of the calculated power by eliminating the coincidence of the maximums of electricity consumption with the maximum of the regional power system. This task also relates to planning the EC schedule or its optimization.

In general, the problem of choosing the optimal power consumption profile to reduce the amount of power can be attributed to the class of one-dimensional problems of integer linear programming.

5 Decision Support System for the Selection of Energy Consumption Models

The results of the study were implemented in a software product on the platform “1C Enterprise 8.3”, which is registered in Rospatent as “Program for optimizing energy costs”, (state registration certificate 2,019,615,052 published. 18/04/2019).

The decision support system for industrial consumers of electricity developed within the framework of this study has tools for creating the necessary calculation models of energy consumption, processing the relevant technical and economic indicators, accounting for production data, as well as tools for analyzing the calculation results and choosing the most profitable energy consumption model that allows you to reduce enterprise costs. In the block diagram (see Fig. 2), these functions are reflected by the corresponding subsystems. The subsystem responsible for making decisions on the choice of calculation models also includes the functions of planning the electricity consumption schedule, since the planned data on the volumes of energy consumption are also used in calculating the cost of electricity consumed for some sets of values of consumer characteristics, with hourly planning.

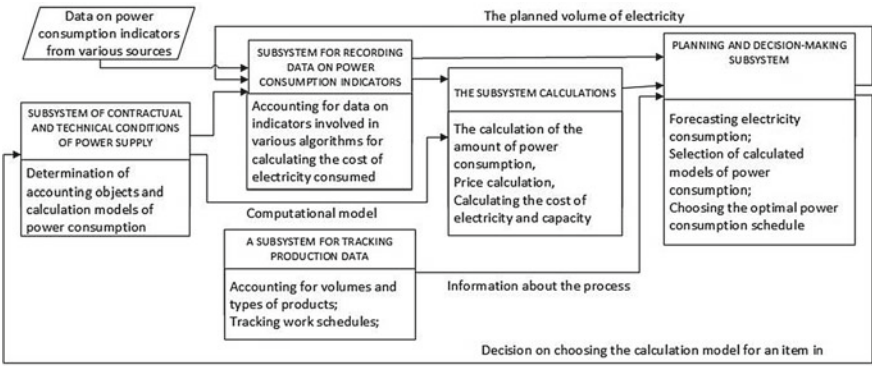

Fig. 2 DSS scheme

6 Conclusion

Thus, as a result of the study, we proposed the method for choosing the most economically profitable calculation model of power consumption for an enterprise. The method includes statistical methods of decision theory and cluster analysis. Also, we developed a DSS, which focused on improving the efficiency of energy consumption management at industrial enterprises by reducing costs for it by choosing the appropriate calculation models of power consumption. The implementation of the DSS at two industrial enterprises showed that the savings from the choice of the calculation model amounted to 13% and 15% per year.

Models and algorithms for processing data on various technical and economic indicators of power consumption implemented in the DSS support accounting for the dynamics of changes in the electricity and capacity market, as well as the ability to build arbitrary calculation models with the required consumer characteristics and calculation rules.

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Averaged Continuous Models of Switch-Mode Power Supplies

Sergey Amelin, Marina Amelina, Sergey Drozdetsky, and Igor Yakimenko

Abstract A general approach to the construction of continuous models of DC-DC voltage converters based on the state-space averaging method is considered. The relevance of the development for universal continuous models of DC-DC converters is substantiated. The typical structure of a switching power supply with feedback is analyzed. An averaged model of the switching structure is proposed, basing on which continuous models of DC-DC converters with any topology can be built. A technique for constructing continuous models based on the proposed averaged model and averaged modulator model is shown. The verification of the proposed model in the frequency and time domain was performed. The results of modeling transients on the continuous and full switch models of inverting voltage regulators are demonstrated. The validity of the continuous models obtained in this way is proved. The possibility of using the same averaged model of the switching structure for building continuous models of converters using both Voltage Mode and Current Mode is represented. This makes the prerequisites for creating a universal continuous model of DC-DC converters on its basis.

Keywords State-space averaging (SSA) · PWM · DC-DC converter · Voltage mode · Current mode

1 Introduction

There are several approaches to the creation of converting device's continuous models. One of them is based on the state-space averaging method [1]. The principle of the method is that the capacitors' voltages and the currents in the inductor coils (state variables) are averaged over the switching period. This averaging occurs taking

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into account the relative duration of all force loop configurations for one period of the clock frequency, i.e., for one period of energy redistribution between inductive and capacitive storage.

Each type of pulse regulator corresponds to certain configurations of the force loop during the switching period, the duration of these configurations is described by various expressions. Each type of converter requires the creation of its own continuous model. For the main types of pulse voltage regulators, buck, boost, and inverting (buck-boost) ones, such models were created long ago and are included in standard libraries of circuit simulation programs. However, new topologies of pulse voltage regulators are constantly being developed, therefore, it is relevant to the search for ways to create a universal continuous model that can be used to describe the operation of any regulator of such type or at least a significant part of these regulators. Vorperian was one of the first to develop such models [2]; there are Basso's and Ben-Yaakov's [3] models for basic converters, but a universal model has not been possible to be created yet.

This chapter proposes an algorithm for creating a model that can be used for several types of DC voltage regulators, including those with complex topologies (SEPIC, CUK), both with classical voltage feedback (Voltage Mode) [4] and with control by the amplitude value of the current for the power switch (Peak Current Mode) [5, 6]. The development of a universal approach to the construction of a continuous model for a DC-DC converter is an urgent scientific and practical problem.

2 Research Objective

This chapter proposes an algorithm for creating a continuous switch-mode power supply model based on the averaged model of a switching element proposed by the authors. A typical structure of a switch-mode power supply with voltage feedback is shown in Fig. 1.

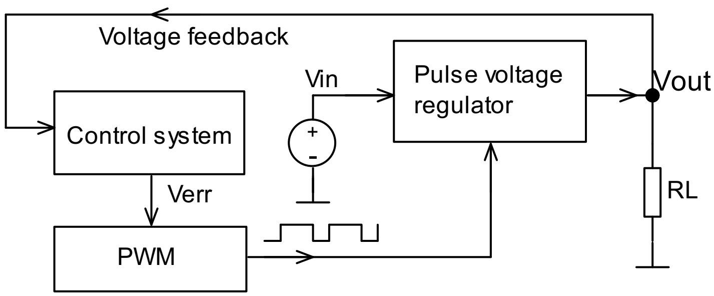


Fig. 1 Simplified block diagram of a switch-mode power supply with voltage feedback (Voltage Mode)

In Fig. 1, the following symbols are used: Verr—error signal; Vin—input voltage; Vout—output voltage; RL—load resistance.

Substantially non-linear links are included in the pulse-width modulation (PWM) and pulse voltage regulator. Therefore, it is necessary to build a specialized continuous model for these elements of the switch-mode power supply structure. The rest of the structural elements are nonlinear continuous links (their transfer characteristics are described by continuous functions).

The approaches to creating a continuous PWM model are described in [7–10] in detail. It also shows the possibility of using a single averaged model of a switching SDL structure for building continuous models of three main types of pulse voltage regulators (BUCK, BOOST, and BUCK-BOOST). This structure includes a controlled switch S, an uncontrolled switch D (diode), and a storage inductor L (Fig. 2).

Unfortunately, models of other regulators types (except for the three listed) cannot be created using averaging the SDL structure. However, it is easy to notice that in all three types of regulators under consideration, the inductor L is connected to the point at which the controlled switch S and the uncontrolled switch D are connected, i.e., to the common switch point (CS). This allows for further generalization–to exclude the inductor from the composition of an integrated averaged model (Fig. 2). Averaging, in this case, is carried out only for the circuits of switching elements (switches). The result of averaging is a continuous model of the SD-structure, which is constructed using the state-space averaging method [1]. The block diagram of the model is shown in Fig. 3.

For the SD-structure, the average current of the controlled switch S in the continuous and discontinuous mode (CCM and DCM) with classical voltage feedback (Voltage Mode) can be calculated similarly:

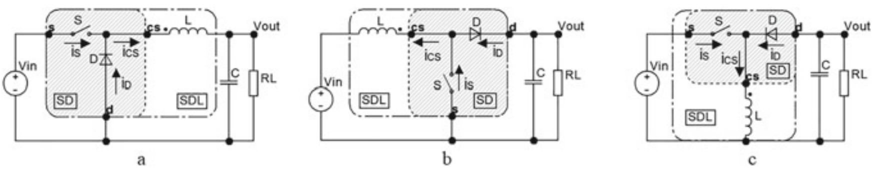
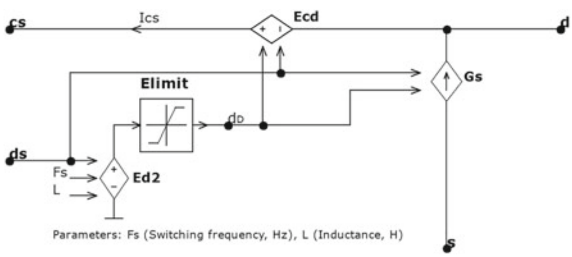


Fig. 2 SDL-structure as a part of the main types of DC-DC converters: **a**—buck; б—boost; **b**—buck-boost

Fig. 3 Equivalent scheme for the averaged continuous model of the SD-structure



$$I_S = I_{CS} \cdot \frac{d_S}{d_S + d_D} \tag{1}$$

where d_S—the relative duration of the conduction for the controlled switch S, d_D—the relative duration of the conduction for the uncontrolled switch D, I_{CS}—average current for the branch connected to the CS point over the switching period.

In the continuous model of the SD-structure (Fig. 3), the average current of the controlled switch I_S is created by a nonlinear dependent current source G_S.

Average voltage $V_{CS,\,D}$ between points "cs" and "d" (average voltage across the diode D) is defined as:

$$V_{CS,D} = V_{SD} \cdot \frac{d_S}{d_S + d_D} \tag{2}$$

where V_{SD}—average voltage between points "s" and "d".

In the continuous model (Fig. 3), the average voltage across the diode $V_{CS,\,D}$ is created by a nonlinear dependent Voltage Source Ecd.

To calculate the relative duration of the diode D conduction, it is necessary to determine the voltage across the inductor when the controlled switch S is turned on through the average values of the voltages of the model external points. For the regulators under consideration, this will be the difference between the average voltages of the points "s" and "cs":

$$V_L = V_{S,CS} = V_S - V_{CS}$$

For the buck converter:

$$V_S = V_{IN},$$
$$V_{CS} = V_{OUT}$$

For the boost converter:

$$V_S = 0,$$
$$V_{CS} = V_{IN}$$

For the buck-boost converter:

$$V_S = V_{IN}$$
$$V_{CS} = 0$$

The relative duration of the diode d_D conduction, in this case, is determined by a relationship similar to that given in [10]:

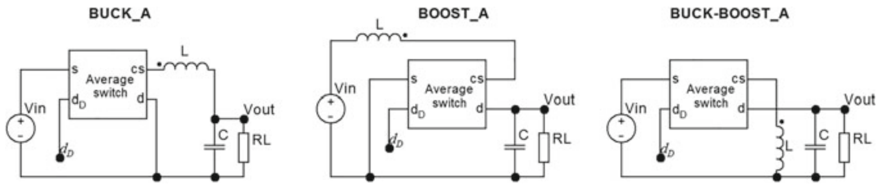


Fig. 4 Continuous models of basic regulators for the Voltage Mode

$$d_D = \frac{2 \cdot I_{CS} \cdot L \cdot f_S}{V_{S,CS} \cdot d_S} - d_S \tag{3}$$

where L—inductance, f_S—switching frequency.

In this case, if the d_D value obtained from (3) turns out to be greater than (1—d_S), then this will mean that the converter is in the CCM. For this mode, the following ratio will be fulfilled:

$$d_D = 1 - d_S$$

Then the final expression for calculating d_D will be as follows:

$$d_D = \min\left\{\left(\frac{2 \cdot I_{CS} \cdot L \cdot f_S}{V_{S,CS} \cdot d_S} - d_S\right), (1 - d_S)\right\} \tag{4}$$

In a continuous model, the d_D value is given by a non-linear dependent voltage source Ed2. Since the relative duration of the conducting state of the diode d_D is always in the range from 0 to 1, the model includes a corresponding Elimit double-sided limiter.

The obtained continuous averaged model of the SD-structure is easy to implement using either universal modeling programs or specialized circuit analysis programs. The equivalent circuit is shown in Fig. 3 was implemented in the Micro-Cap circuit analysis program. To simplify the work with the equivalent circuit, it is advisable to represent it as a component with S, D, CS, and d_D outlets. The inductance value L (H) and the switching frequency f_S (Hz) are set as parameters. Continuous models of the three basic regulators using the Average switch model are shown in Fig. 4.

3 Verification of the Proposed Model in the Frequency and Time Domain

To create a continuous model of a switching power supply, it is necessary to implement a control circuit through a simulation program, which is a trivial task, and connect a continuous Average switch model to it. A block diagram of a continuous

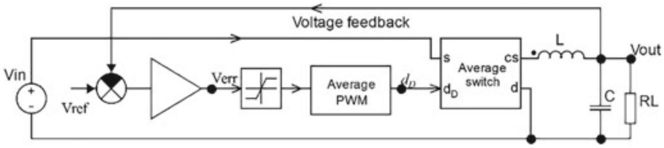


Fig. 5 Structure of a continuous model of a switched-mode converter based on a buck regulator

voltage regulator based on a buck (BUCK) regulator for Voltage Mode is shown in Fig. 5. A block diagram of a continuous model of a switched-mode converter based on a buck regulator for the Voltage Mode is shown in Fig. 5.

To implement control by the Peak Current Mode, it is reasonable to use the corresponding continuous Average switch model; it is only necessary to insert a link for converting the switch amplitude current into the duty cycle dS. In this case, the averaged model of the SD-structure (Average switch) remains unchanged.

The adequacy of the constructed models for the basic regulators can be checked by comparison with experimental data or comparison with the simulation results for the complete (switch) model of the corresponding switch-mode power supply. Figure 6 presents the results for modeling the transient processes of reaching the steady mode at the duty cycle constant value of the control switch d_S. The upper graph shows the output voltage V_{OUT}, the lower graph shows the inductor current I_L. In Fig. 6 black lines correspond to the key model, grey lines correspond to the continuous model. The output voltage ripple is purposely selected large enough for clarity.

From Fig. 6 it is obvious that the constructed model adequately reflects the behavior of the constant components of the circuit state variables (inductor current and capacitor voltage) both in the CCM and DCM. Ripples information is naturally lost when using the continuous averaged mode.

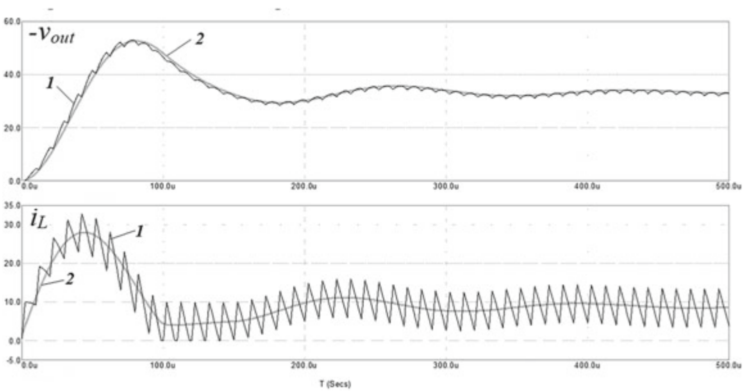


Fig. 6 Oscillograms for the output voltage—Vout and the inductor current i_L at the output of the inverting converter (BUCK-BOOST) to the steady mode at a constant duty cycle d_S: 1–switch model; 2–continuous model

Using the constructed continuous models, control characteristics can be obtained for an ideal converter and for a regulator with losses [11, 12]. The active resistance of the switches and the storage inductor can be easily included in the continuous model in the form of active resistance in the corresponding branches. In this case, the efficiency of the switch-mode power supply is possible to be calculated. But the most important thing is that according to the constructed model, the amplitude-frequency and phase-frequency characteristics of the open path “control—output” can be obtained, which is very important for the analysis of the stability of the closed-loop stabilization system [13, 14].

To verify the constructed model of the converter in the frequency domain, it is necessary to compose the equations for currents and voltages averaged over the switching interval, carry out manual linearization and obtain transfer functions in an analytical form.

The averaged nonlinear system of equations for the buck-boost converter (Fig. 2c) in the continuous current mode of the inductor, taking into account the parasitic resistances of the inductor and capacitor, has the following form:

$$\begin{cases} d_S \cdot v_{IN} = L \cdot \dfrac{di_L}{dt} + i_L \cdot R_{DCR} + (1 - d_S) \cdot (v_C + i_C \cdot R_{ESR}) \\ i_L \cdot (1 - d_S) = C \cdot \dfrac{dv_C}{dt} + \dfrac{v_C + C \cdot \frac{dv_C}{dt} \cdot R_{ESR}}{R} \end{cases} \tag{5}$$

where i_L—inductor current, $R_{DCR,}$ and R_{ESR}—parasitic resistances of the inductor and capacitor, correspondently, v_C and i_C—voltage and capacitor current, correspondently.

For manual linearization of the equations system in the area of the operating point, it is necessary to present the averaged values of the duty cycle, currents, and voltages as the sum of a small-signal disturbance and a stationary component

$$\begin{aligned} &d_S \Rightarrow \tilde{d}_S + D_S \\ &v_{IN} \Rightarrow \tilde{v}_{IN} + V_{IN} \\ &L \cdot \frac{di_L}{dt} \Rightarrow L \cdot \frac{d(\tilde{i}_L + I_L)}{dt} = L \cdot \frac{d\tilde{i}_L}{dt} \\ &d_S \cdot v_{IN} \Rightarrow \tilde{d}_S \cdot \tilde{v}_{IN} + \tilde{d}_S \cdot U + D \cdot \tilde{v}_{IN} + D \cdot U \end{aligned} \tag{6}$$

After substituting the summands from the system (6) into (5) and passing to the operator form:

$$\begin{cases} \tilde{d}_S \cdot \tilde{v}_{IN} + \tilde{d}_S \cdot V_{IN} + D_S \cdot \tilde{v}_{IN} + D_S \cdot V_{IN} = \\ = L \cdot s \cdot \tilde{i}_L + \left(\tilde{i}_L + I_L\right) \cdot R_{DCR} + \left(1 - \tilde{d}_S - D_S\right) \\ \cdot\left(\tilde{v}_C + V_C + \left(\tilde{i}_C + I_C\right) \cdot R_{ESR}\right) \\ \left(\tilde{i}_L + I_L\right) \cdot \left(1 - \tilde{d}_S - D_S\right) = C \cdot s \cdot \tilde{v}_C + \dfrac{\tilde{v}_C + V_C + C \cdot R_{ESR} \cdot s \cdot \tilde{v}_C}{R} \end{cases} \tag{7}$$

Various transfer functions can be expressed from the system (7). For example, the characteristic "duty cycle–output voltage" is as follows:

$$\frac{\tilde{v}_{OUT}}{\tilde{d}_S} = \frac{\left(-\frac{LV_{OUT}}{R(1-D_S)^3}s + \frac{V_{IN}}{(1-D_S)^2}\right) \cdot (1 + R_{ESR}Cs)}{\frac{(R+R_{ESR})LC}{(1-D_S)^2R+R_{DCR}}s^2 + \frac{L+(R+R_{ESR})R_{DCR}C+(1-D_S)^2RR_{ESR}C}{(1-D_S)^2R+R_{DCR}}s + 1}$$

The obtained function contains right-half-plane zero [15], the link having such a characteristic is a non-minimum phase [16]. Also, the transfer function contains a double resonant pole and a left-half-plane zero provided there is RESR. Frequency response characteristics of the function "duty cycle–output voltage" are given in Figs. 7 and 8.

To synthesize the Current Mode control system, an "input current-output voltage" characteristic is required [17, 18]. The input current and inductor current of the inverting converter in the Continuous conduction mode are related by the ratio:

$$i_{IN} = i_L \cdot d_S$$

The sum of the small-signal disturbance and the stationary component of the input current in the Continuous conduction mode is determined by the expression:

$$\tilde{i}_{IN} + I_{IN} = \left(\tilde{i}_L + I_L\right) \cdot \left(\tilde{d}_S + D_S\right) = \tilde{i}_L \cdot \tilde{d}_S + \tilde{i}_L \cdot D_S + I_L \cdot \tilde{d}_S + I_L \cdot D_S \tag{8}$$

To find the ratio of the input current disturbance to the duty cycle disturbance, the stationary components are necessary to be excluded from (8). The product of small disturbances tends to zero, so it should also be excluded from (8). Then the ratio for the small-signal disturbance of the input current takes the form:

$$\tilde{i}_{IN} = \tilde{i}_L \cdot D_S + I_L \cdot \tilde{d}_S \tag{9}$$

The transfer function "input current-output voltage" can be obtained from (7) taking into account (9):

$$\frac{\tilde{v}_{OUT}}{\tilde{i}_{IN}} = \frac{RV_{IN}}{V_{OUT}} \cdot \frac{(1 + R_{ESR}Cs)}{(1 + RCs)}$$

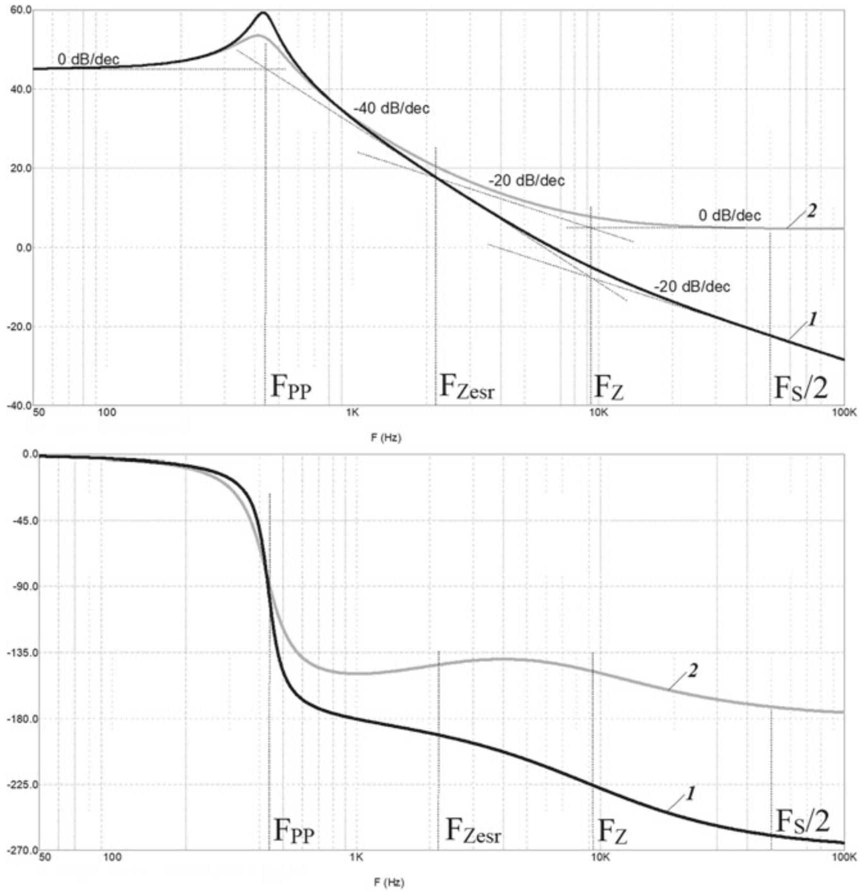


Fig. 7 Logarithmic amplitude-phase frequency response characteristic (Bode Plot) and Logarithmic phase response frequency characteristic for the "duty cycle- output voltage" transfer function of the inverting regulator taking into account parasitic resistance: 1—$R_{ESR} = 0$; 2—$R_{ESR} \neq 0$

The coincidence of the frequency characteristics obtained using the model in Micro-Cap and using analytical expressions allows concluding that the model is built correctly.

The resulting averaged model of the SD-structure (Average switch) can also be used to build continuous models for voltage converters with complex topology, for example, the Ćuk converter [19, 20]. Figure 9 shows the structure of its continuous model, obtained on the basis of the developed averaged structure:

The results of comparing the results obtained in the simulation by the complete (key) model and by the continuous model show a complete coincidence of the envelopes of the transient process for all state variables: the voltages of the capacitors Cs, Cp (Vout), and the inductor currents (Ls, Lp).

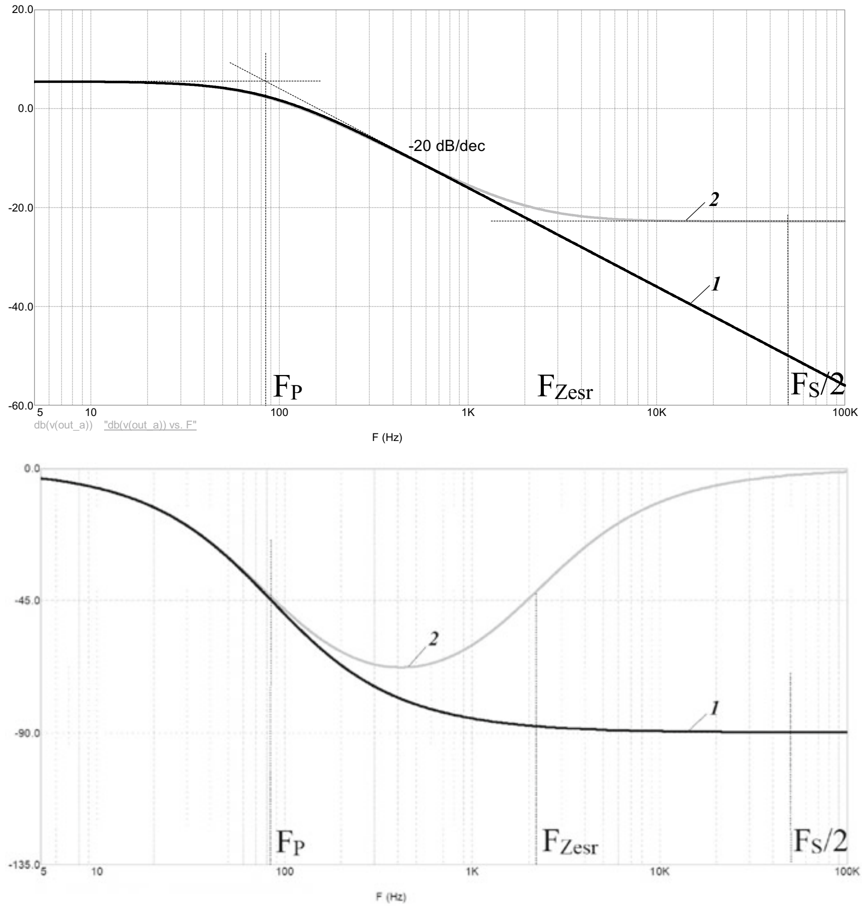


Fig. 8 Logarithmic amplitude-phase frequency response characteristic (Bode plot) and Logarithmic phase response frequency characteristic for the "input current- output voltage" transfer function of the inverting regulator taking into account parasitic resistance: 1—$R_{ESR} = 0$; 2—$R_{ESR} \neq 0$

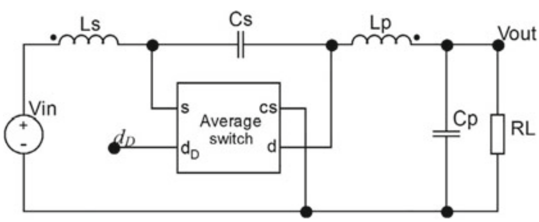


Fig. 9 Continuous model for the Polikarpov—Ćuk converter

4 Conclusion

An averaged model of a switched PWM structure is proposed and verified, which makes it possible to obtain models of DC-DC voltage converters with any, including previously unused topology.

It is shown that the model can be modified to describe DC-DC converters in other control modes different from the Voltage Mode.

Various characteristics in the frequency domain are obtained, which correctly describe the behavior of the buck-boost converter up to half of the switching frequency for the power switch.

Further development of the averaged SD-structure model presented in the chapter is its adaptation for the Peak Current Mode control and the creation of a universal averaged PWM modulator model capable to implement both Voltage Mode and Current Mode. This is enough to create a universal averaged model of a switched-mode voltage converter with any topology of the power part and any control method.

At the stage of a switch-mode power supply construction, such a model will allow synthesizing the necessary compensation circuits [21, 22] and, as a result, obtaining the necessary dynamic parameters of the finished device.

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Development of a Software and Hardware Stand for Aerodynamic and Electromechanical Characteristics Calculation of a Vortex Type Wind-Driven Power Plant

V. A. Kostyukov, A. M. Mayevsky, and N. K. Poluyanovich

Abstract This chapter discusses a software and hardware complex for the study of aerodynamics and electromechanical characteristics of wind-driven power plants (WP) with a vertical axis of rotation. A vertical-axis wind-driven power plant, which is a cyber-physical system (CPS), for additional and emergency power supply of surface robotic systems, was considered. The created laboratory stand for experimental research of the developed wind-driven power plants, and WP prototypes with a capacity of 0.2 and 1.2 kW are considered. The developed software makes it possible to numerically simulate the WP motion under conditions of an unsteady undisturbed wind flow, considering the mass-inertial characteristics of the installation. In particular, it allows one to study the processes of considering type WP starting and stopping, as well as the reaction of the installation to a wind impulse load, wind gust. The experimental and numerical results obtained using the developed software and hardware complex are compared. These results indicate the possibility of using developed hardware and software complex as an effective tool for the WP development with a vertical axis of rotation.

Keywords Wind-driven power plant · Cyber-physical system · Experimental research · Software and hardware complex · Numerical modeling · Numerical methods of continuous media dynamics

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1 Introduction

Currently, there is a large group of land-based and offshore facilities, stationary-based and mobile, including robotic systems, in need of auxiliary autonomous energy sources [1]. One of the promising development directions of such sources is the development of wind-driven power plants that effectively cover a significant part of the energy costs of these facilities with appropriate restrictions on reliability and cost [2].

The indicated WP can be applied both based on the stationary platform and the basis of the mobile one–see Fig. 1a, b.

Such wind-driven power plants can be used as power supply systems: structures located on the sea shelf [3, 4]; autonomous underwater vehicles (AUV) [5]. The use of these sources together with the technology of AUV remote servicing [6] without the need for ground support or complex cable systems [7], can significantly reduce the labor intensity and cost of maintenance of facilities on the sea shelf or AUV.

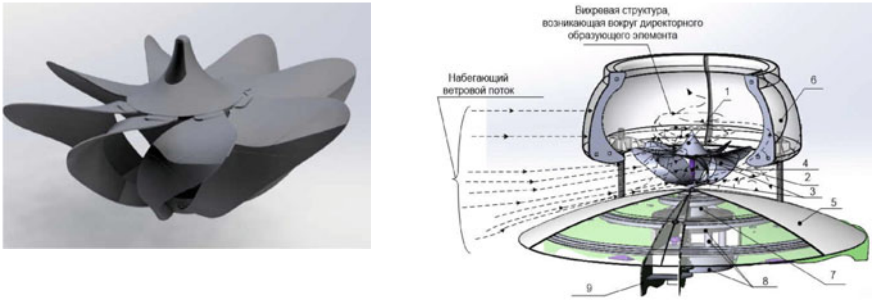
One of the important criteria for selecting the most suitable for the use WP type is, on the one hand, the wind energy use coefficient in the working range of its speeds, on the other–the WP installation cost on a supporting platform, which may allow, to a greater or lesser extent, the possibility of such an installation without affecting the output characteristics of the entire device.

The first criterion is relevant for both stationary and mobile platforms; the second is of predominant importance for mobile objects since the latter are subject to more serious restrictions on the dimensions, weight, windage of the additional WP structure concerning stationary platforms. In this regard, vertical-axis WP has a significant advantage over horizontal-axis WP. Known installations of the vertical-axis type with Savonius type or Darrieus type rotors [8]; in works [9] one of the possible promising vertical-axis rotary type WP (see Fig. 1a) with its possible applications for power supply of various types of platforms (see Fig. 1b, c) is analyzed.

a) use of the developed WP in the complex power plants for autonomous boat supply

b) use of the developed WP for autonomous docks supply and basing stations for underwater vehicles

Fig. 1 Possible mobile platforms for the developed WP



a) the appearance of the vortex-type WP rotor

b) the principle of the vortex-type WP operation

Fig. 2 Consideration of the promising vortex-type WP

The operation of such installation is based on the principle of useful aerodynamic interference between its static and rotor parts, as well as the use of special shape rotor blades (see Fig. 2a), which effectively perceive both horizontal and vertical ascending flows. The vortex resulting from the rotor rotation is concentrated inside the diffuser and above its upper part. The resulting low-pressure areas cause the effect of additional thrust, which increases the rotor torque. The vortex structure arising above it additionally feeds the rotor with energy, being in dynamic equilibrium with it (see Fig. 2b).

In [10], the results of stator shape aerodynamic optimization of the vortex-type WP according to the criterion of the maximum aerodynamic power on its shaft are presented, which made it possible to increase the indicated power by more than 20%, all other things being equal, compared to the original stator shape.

In [11], the aerodynamic control system for the angular rotation speed of WP rotor indicated vortex type is considered based on the use of variable geometry elements of the installation structure. The latter is the adjustable distance from the lower guide structure to the lower rotor edge and the extension degree of the brake flap, installed on the upper part of the WP stator outer surface and playing the role of an aerodynamic brake.

In this chapter, a laboratory stand and prototype installations are considered, which make it possible to experimentally study rotary-type WP of various modifications, as well as to verify their virtual blowdowns results. The block diagram of the WP control device's main elements connection is given.

The precision mechanics development, including technologies for manufacturing actuator drives, together with an efficiency increase and aerodynamic analysis depth of the processes occurring during the WP operation, can eventually make the method of angular speed aerodynamic control the main one for some WP types.

The studies of articles [11, 12] were largely based on the methods of continuous media computational dynamics (CFD–modeling). However, there the process of WP aerodynamics modeling was not considered together with the mechanic's calculation of its WP rotor motion in a unified computational software environment.

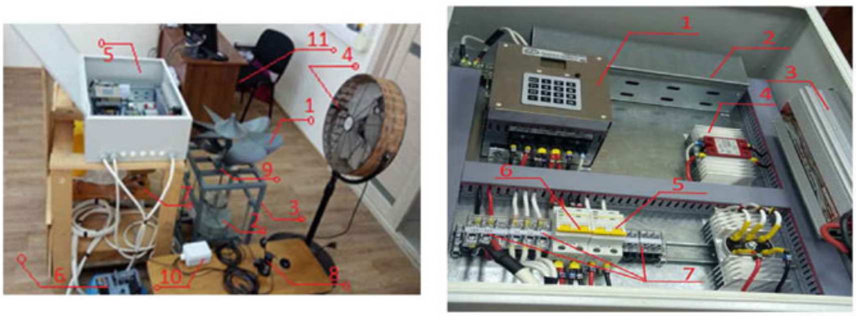
This chapter also considers a software package that allows numerical simulation of WP motion from a unified point of view based on an equations system for finite differences connecting mechanical, including aerodynamic, effects with the corresponding displacements of the mechanical system elements, considering its mass-inertial characteristics and the environment properties.

2 Experimental Study of the Vortex-Type WP

Within the framework of the study of the vortex-type WP considered above, a laboratory stand was created to study the electromechanical characteristics of wind-driven power plants with powers up to 1 kW.

This stand for aerodynamic and electromechanical WP tests, the appearance of which is shown in Fig. 3a, includes a WP rotor 1 with a generator 2, fixed on a single supporting structure 3; fan for blowing air 4 to simulate wind blowing; control unit for 5 operating modes and WP output characteristics, storage battery 6 with nominal 60A*h; electrical load 7 in the form of incandescent bulbs with a total power of 80 W; anemometer 8 for measuring the wind flow speed; installed Hall sensor magnet 9; board 10 for control and recording of the sensors 7 and 8 readings; operator's workstation 11, on the monitor of which the wind flow current speed, the WP rotor angular rotation speed, voltage and current at the load are displayed in real-time.

The external view of the control unit device is shown in Fig. 3b. Here: 1—the battery charge controller; 2—the ballast resistance, where excess power is dumped when the maximum possible rotor angular speed is exceeded; 3—the inverter; 4—the solid-state relay used in the electromagnetic braking system; 5—the automatic switch



a) the external view of the laboratory stand for WP aerodynamic and electromechanical tests

b) electronics of the wind wind-driven power plant control system

Fig. 3 Laboratory stand for verification of aerodynamic and electromechanical WP models and their equipment

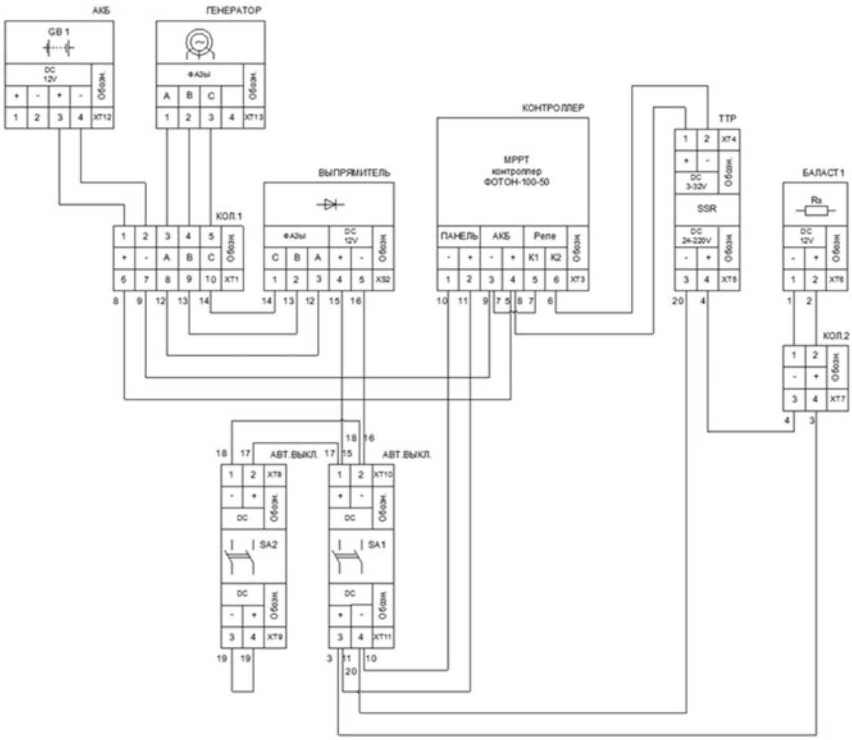


Fig. 4 Block diagram of WP control device main elements connection

for manual system shutdown, both for manual braking and temporary shutdown during repair; 6—the automatic switch for switching between automatic control of the controller and manual control mode; 7—the connecting blocks.

Figure 4 shows a block diagram of the connection of WP control device main elements. The device, according to the indicated scheme, works as follows. The alternating signal from the generator goes to the rectifier, from which almost constant voltage is removed, supplied to the battery charge controller–MPPT controller "Foton–100–50".

The latter maintains the voltage on the battery in real-time in the specified ranges corresponding to the properties of the battery. In this case, if the power at the rectifier output exceeds the threshold value corresponding to the upper limit in terms of power for normal battery operation, surplus power is released to the ballast resistance through a solid-state relay triggered by the controller and playing the role of an intermediate amplifier of its signal. The power removed from the battery goes to the load.

For experimental full-scale verification of the optimization aerodynamic calculations carried out and subsequent testing of the developed control system, two prototypes were developed: first has a rated power P1nom = 0,2 kW at a rated wind speed

a) low power WP testing $P_1 = 0{,}2kW$ (at a nominal wind speed of 7 m/s) on a car platform

b) greater power WP testing $P_2 = 1{,}2kW$ (at a nominal wind speed of 7 m/s)

Fig. 5 Field tests of low ($P_{1nom} = 0{,}2\ kW$)–**a**, and great ($P_{2nom} = 1{,}2\ kW$)–**b**, WP power

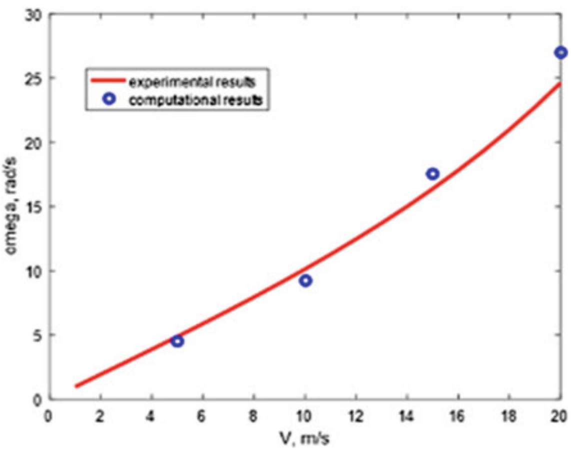
Vnom = 7 m/s, the second has a power P2nom = 1,2 kW at the same rated wind speed. Justification of the rotor aerodynamic efficiency used in these installations is given in [9, 10].

Figure 5 a shows the appearance of a mobile platform with a WP mock-up model installed on it with a capacity P1nom = 0,2 kW, and Fig. 5 b shows an external view of an installation with a capacity P2nom = 1,2 kW.

Preliminary tests of the model were carried out to clarify the requirements for the electrical and electromechanical elements of the installation, first of all, the generator.

Figure 6, the red line shows a graph of the approximate experimental dependence of the steady-state angular WP speed ω(V) on the wind speed V under the following conditions: the rotor diameter D = 600 mm and height H = 310 mm and the moment of inertia reduced to the rotor axis J = 0,03 kg*m^2, the rotor blades material is ABS

Fig. 6 Comparison of the static dependencies of the steady rotor angular speed on the constant wind speed obtained experimentally (red curve) and numerically (blue dots)



plastic, the connected electrical load with rated power Pn = 80 W; the blue dots represent the corresponding results of the CFD analysis, discussed further in Sect. 3; the latter deviate from the experimental values by no more than 10.5%.

One of the reasons for the deviations of the numerical results from the corresponding experimental ones is not considering in the modeling complex the moment of the opposite EMF, which arises due to the presence of WP electric load.

3 A Software Module Development for Studying WP Aerodynamic Properties in an Unsteady Wind Flow

Formulation of the problem. Most research on WP aerodynamics is based on CFD methods, which imply the solution of a pseudo-stationary problems variety with a fixed wind speed. They are usually based on the concept of the sliding grid. This method is used, in particular, in [13]—for modeling the dynamics of a horizontal-axial hydraulic turbine; in [14]—to compare the numerical studies of a horizontal-axial three-blade turbine with its corresponding tests in a wind tunnel; in [15, 16]—to study WP aerodynamic characteristics with a Savonius-type rotor.

The use of methods that allow simulating WP dynamics considering the influence of the turbine mass-inertial characteristics and the resistance moments on its shaft is much less represented [17, 18]. Here, as a rule, a combined Euler–Lagrange approach is used, which makes it possible to model, among other things, the changing grid structures (dynamic grids) of the computational domain, as well as to track and consider the movements of individual particles of the medium in the areas of this domain that are most critical for local sites modeling accuracy.

It is based on the latter method that a fairly strictly unified process of WP starting, its entry into a steady-state and subsequent deceleration, caused by a change in wind speed, considering the given dynamic parameters of the turbine and the parameters of resistance to its rotation from the side of the medium, can be considered.

Consider a software module developed by the authors based on the Ansys Fluent software environment that allows evaluating the interaction between the wind and rigid blades in the process of changing the turbine rotation speed using additional user-defined files (UDF files) that take into account the mass-inertial characteristics of WP turbine and environment parameters and to simulate the nature of the change in WP turbine from the moment of its start until the turbine reaches its final angular rotation speed.

In addition, the aerodynamic optimization developed method of the static and rotor parts of vertical-axial vortex wind power plant [8, 10] made it possible to significantly expand the capabilities of this software package for labor-intensive design of the WP structure based on a given technical task. The basis of this technique is, firstly, the choice of key parameters that determine the aerodynamic quality of this type WP rotor: three geometric parameters characterizing the blade profile and the distortion degree of its geometry from the original [8]; secondly, an algorithm for choosing a sufficiently representative set of basic topological forms of stators, and each such basic form generates its branch of research on parametric optimization [8, 10].

Such developed software modules as the input geometry preprocessing, the type choice of the solver for the system of gas-dynamic equations, and the block for post-processing of the obtained modeling data, are adapted by default specifically for the case of the considered promising vortex WP; although the program interface makes it easy to reorient the settings for other types of investigated installations.

We will proceed from the following law of WP rotor rotation [9, 11]:

$$J\frac{d\omega}{dt} = M(V, \omega) + M_c(\omega) \tag{1}$$

where V—the wind speed, changes of which represent in this problem an external disturbance; J—the reduced moment of the rotor inertia; M (V, ω) + Mc (ω)—the useful aerodynamic torque on the rotor and load torque.

Law (1) indicates that pure external torque on a rigid body will cause angular acceleration. The rigid body rotation will accelerate until the total torque is zero or periodically fluctuates around zero.

It is necessary to develop a software complex for modeling WP vortex-type aerodynamic characteristics in non-stationary modes of wind speed changing. It must be tested for the following specific data: Moment of the rotor inertia shown in Fig. 2a, J = 0,03 kg/m2, the rotor midsection S = 0,0223 m^2, the dependence of the resistance moment on the rotor shaft to its rotation is a function: Mc (ω) = bω, where b = 0,573 H*m*s; the choice of the function is based on the results [9, 11].

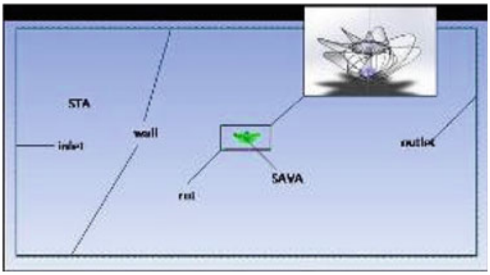
3.1 The Method Used and Its Application

First of all, a computational domain was constructed, in which the fields of key aerodynamic quantities, first of all, pressure and speed, will be located. The diagram of the computational domain is shown in Fig. 7a. It should be noted that the origin of coordinates is set at the gravity center of the WP rotor.

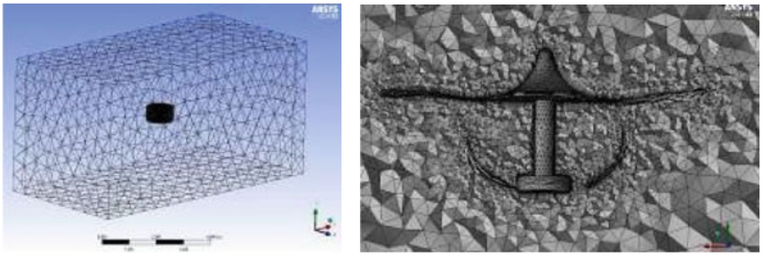
This diagram shows the main elements necessary for calculating WP aerodynamic characteristics: the flow inlet and outlet zones, the rotation (rot) area and WP blades included in it, the stationary region (STA), and the outer boundaries of the computational domain (wall).

The computational domain, the rotor wall layers, and the rotating structure are shown in Fig. 7b; the parameters of the resulting grid are as follows: the number of grid elements–1,338,491; the number of wall layers–10; the average cell orthogonality index is 0.71. The *k-epsilon-realizable* model was used to calculate turbulent phenomena.

To study the WP characteristics under the non-constant influence of the incident flow ($V \neq const$), it is necessary to create two special user-defined functions, the first



a) diagram of the computational domain



b) WP grid model and the computational domain

Fig. 7 To the construction of the computational domain grid division

of which describes the temporary change in the speed of the unperturbed flow when entering the computational domain, and the second describes the dependence of the moment of rotor shaft resistance on the angular speed.

The modeling complex operation, which allows, in addition to the aerodynamic effect, to consider the rotor inertial properties and the resistance moment on its shaft, is represented by the following key stages:

1. The main *CFD* study of the model aerodynamic characteristics is carried out based on the viscous fluid motion equation (RANS), taking into account the input characteristics of the incoming flow speed (V), the simulation time t, the time step (Δt), the inertial WP characteristics (mass and moment of inertia), the moment dependence function resistance from angular speed M_c (ω).
2. At each i-th step, the total moment of force M_i acting on the WP rotor is calculated, which is formed from the body interaction moment with the incoming airflow, in the general case, the speed variable in time, and the resistance moment on the rotor shaft, set from the outside; in this case, the angular speed of the body rotation ω_i, achieved at the i-th step, is taken into account:

$$M_i = M_c(\omega_i) + M_a[V(t_i), \omega(V(t_i))] \tag{2}$$

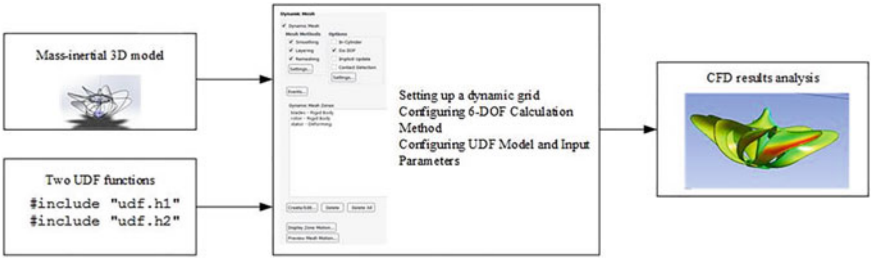


Fig. 8 Block diagram of the developed software complex

3. The angular speed value is calculated at the next step $t_{i+1} = t_i + \Delta t$ using the difference formula following from (1):

$$\omega_{i+1} = \omega_i + (M_i/J)\Delta t$$

4. Based on the new rotation speed $V(t_{i+1})$ of a rigid body, a new flow field is modeled according to discrete difference equations corresponding to the differential equations of continuous medium motion (Navier–Stokes equations) considering the given boundary conditions.
5. Repeat the above procedures 1–4 until the process research time interval has been exhausted.

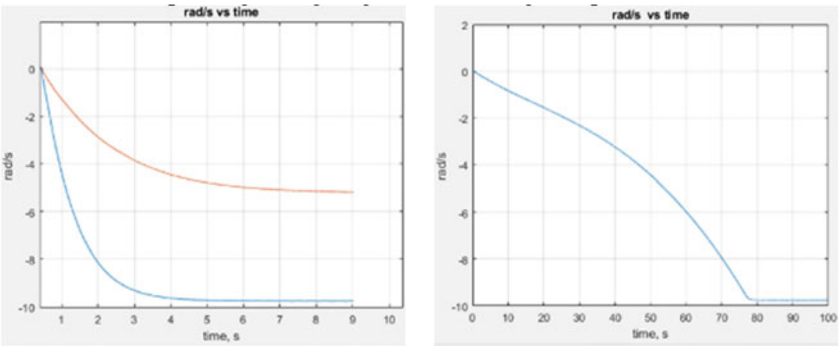
Note that at each time step ti, the solver performs an additional iterative procedure for instant solution finding with discrete pseudo time, which makes it possible to achieve acceptable calculation convergence for a given one ti.

The general block diagram of the modeling complex operation, which describes the interaction process of the WP rotor with an unsteady incoming gas flow in the presence of a moment of resistance on the rotor shaft, is shown in Fig. 8.

The input data for calculating WP rotation are the functions of changing the incoming flow speed, the dependence of the resistance moment on the shaft on the angular speed as well as the mass-inertial WP characteristics. Further, in the block of settings for the CFD and 6-DOF model (calculating block for body dynamics with six freedom degrees), the basic settings for the rotation system and dynamic meshes deformation are formed. To organize the rigid body free, rotation an axis was chosen that coincided with the rotor rotation axis, after which the main rotation objects (rotor, rotor rotation area, general computational area) were adjusted.

3.2 Simulation Results

Let us consider the results of solving the problem by the method described above, at a constant wind speed $V = 10\ m/s$ and the condition of the rotor initial rest. Figure 9a shows the corresponding timing diagrams for the angular speed ω in this case.



a) b)

Fig. 9 Timing diagrams of the rotor rotation angular speed at the initial rest of the rotor and: **a** constant wind speed; **b** unsteady incoming flow, varying according to (4)

As the graphs are shown in Fig. 9a, at the wind speed V = 5 m/s, the angular speed ω reaches saturation approximately by the time instant t = 7,5 s (with a saturation value approximately equal $\omega = 5,1\, rad/s$); at the wind speed, V = 10 m/s, ω reaches saturation at about the moment of time t = 4,0 s (with a saturation value approximately equal $\omega = 9,8\, rad/s$) that when approaching the saturation region, the graphs oscillate slightly. A negative value is associated with the selected direction of the axis of rotation.

Note that the time diagrams of the angular rotor rotation speed shown in Fig. 10a, agree well in terms of the steady-state values of the angular speed with the corresponding experimental results with a maximum relative deviation of up to 5%.

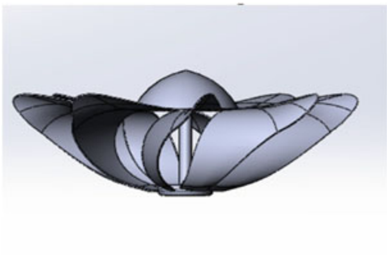
Now let us consider the calculation results with the following dependence of the incident flow speed on time:

$$V(t) = \max[e^{0,03t}, V_{\max}] \tag{4}$$

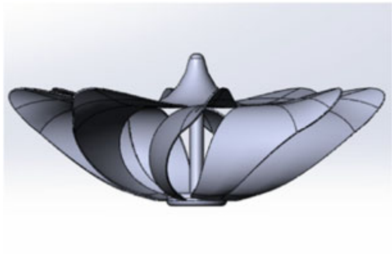
where the upper limit was imposed on the value of the input flow rate equal to Vmax = 10 m/s. Figure 8b shows the corresponding timing diagram for the angular speed ω in this case.

From an examination of Fig. 9b, it can be seen that WP time to reach the steady-state value of the angular speed ω = 9,71 rad/s reaches the value t = 75 s.

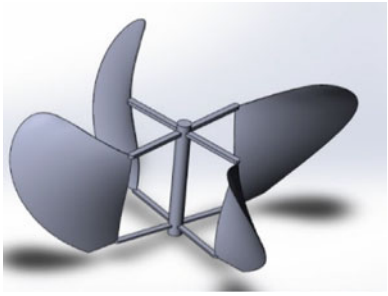
The simulation results, including those presented in Figs. 6 and 9, allow us to conclude that the developed software and hardware complex allows the correct calculation of the impact on WP of both stationary undisturbed airflow and unsteady airflow. The latter can be effectively used to study the WP operation process from the moment of start-up to shut down when the wind speed decreases to a certain critical value [19, 20].



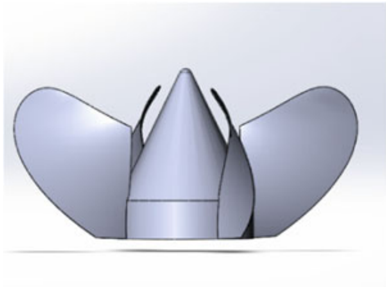
a) rotor with initial RGE - option 1



b) rotor with optimized RGE - option 2



c) modernized rotor with changed blades - option 3



d) modernized rotor with changed blades and RGE - option 4

Fig. 10 Rotor designs: the original rotor with an additional non-optimized **a** and an optimized RGE **b**, a rotor with modified blades without an RGE **c**, and with an RGE **d**

To check the aerodynamic optimization possibilities of the WP design using the created software package, a rotor with an additional guiding element located axisymmetrically above the original rotor shape was taken; the shape of this element is close to a hemisphere, see Fig. 10a. Further, it was optimized according to the criterion of the maximum aerodynamic moment on the rotor shaft. As a result, a new shape of the rotor guiding element (RGE) was obtained according to Fig. 10b, which made it possible to increase the torque on the rotor by 12%.

Further, the developed software package made it possible to find a new basic topological shape of the rotor and carry out its corresponding parametric optimization, as a result of which it was possible to increase the torque on the WP rotor by another 46% compared to option 2 (see option 3 on Fig. 10c). Then a guiding element with an initial spherical shape was introduced, which was further optimized in shape to obtain a tapered RGE. The last modernization made it possible to increase the torque on the rotor by 10% in comparison with option 3 (see option 4 in Fig. 10d).

4 Conclusion

The developed software package can be effectively used to study the interaction of an incoming airflow and the WP solid body in the unsteady undisturbed flow mode and the presence of the resistance moment on the rotor shaft, which depends on its rotation angular speed. This complex makes it possible to perform calculations considering nonlinear flow disturbances described by custom functions, which significantly increases the possibilities for theoretical studies of the WP operation. Subsequently, this complex can be expanded considering the use of 2-FSI technology to study WP strength characteristics under the influence of a gas flow, taking into account its free rotation.

At the same time, this software package capabilities for aerodynamic optimization of the WP shape structure, both stator, and rotor, make it possible to use this complex not only at the stage of verification of already manufactured WP but also at the earliest stages of their development. Moreover, the indicated modeling capabilities at the development stage and verification of already manufactured WP structures are specialized and adapted in this complex for promising vertical-axis WP. This is the novelty and practical significance of this software product, considering the accelerated growth of the fields of application of vertical-axis wind turbines and the need for their accurate calculation at the stages of design, development, manufacturing, and testing.

The created laboratory stand and mock-up installations allow carrying out experimental studies of rotary-type WP of various modifications, as well as verifying the resulting results of modeling their aerodynamics.

The developed software package was verified by laboratory and field tests of the assembled prototypes.

The specified software, together with the created laboratory stand, allows the effective development of wind-driven power plants with a vertical axis of rotation, as evidenced by a good correlation of the corresponding experimental and numerical results.

The results obtained concerning the method of wind power plants development and verification can be effectively used to create power modules for automated, automatic, cyber-physical systems.

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Subsystem for Building a Digital Twin of the Main and Auxiliary Equipment of Thermal Scheme of Thermal Power Plant

Ivan Shcherbatov, Vladimir Agibalov, Aleksey Dolgsuhev, and Michael Belov

Abstract Digital twins are currently one of the main tools for improving the operational efficiency of the main and auxiliary equipment. In the study, digital twins are used as a basis in predictive analytics systems. The comparison of the current measurement information coming from the sensors with the results calculated in the digital twins of the equipment units provides identification of the current technical condition. In this chapter, we consider one of the possible approaches to implementing the architecture of a software product for building a digital model of a thermal power plant thermal circuit—the allocation of layers. It describes the advantages and disadvantages of this method in designing, changing the source program code, and correcting the internal structure of software—refactoring. The main advantage of the method is scalability since thermal circuits can contain a large number of pieces of equipment. A three-level architectural solution of the digital twin construction subsystem has been developed. A fragment of a database accumulating the required data for obtaining calculated data using a digital double of the thermal circuit of a power plant is presented. It also shows the implementation of one of the abstract layers of the architecture—the database management system layer. The obtained results allow us to assert the effectiveness of the layers method application for use as part of predictive analytics systems using the concept of the main and auxiliary equipment digital twins of energy facilities.

Keywords Digital twin · Software · Database · Modeling · TPP equipment · Life cycle

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1 Introduction

At present, a large number of companies in various industries are resorting to implementing IT-based solutions for various needs. Every year there is an upward trend in this direction. According to the Energy Strategy of Russia until 2024 [1], one of the main objectives is to increase the energy efficiency of energy facilities. This can be achieved not only through design solutions for power equipment or hardware, but also through the introduction of digital technologies such as digital twins [2], predictive analytics systems [3, 4], virtual simulators [5], augmented reality systems [6]. Due to this, there is an avalanche-like increase in the volume of inherited and developed code, which needs support, optimization, timely refinements, and refactoring [7]. This explains the crucial importance of software architecture design and construction. This theme is especially urgent for such strategically important branches of Russia as power engineering, defense industry, medicine, etc. that the life cycle of programs used by them should be the longest. Only a few years ago scientific community and developers all over the world began to pay more attention to software development methodologies. If previously most of the attention was focused on the initial stage of the software life cycle, now analysts and architects are working evenly on each stage of the life cycle.

Recently there has been a breakthrough: great attention has been paid to the systematic use of transformations as a central principle of organizing the existing process of software development and maintenance. However, most researchers treat transformations rather narrowly, as transformations at the source code level. At present, there are almost no studies devoted to the transition to a higher level of abstraction, the level of software architecture [8]. The overwhelming majority of development and maintenance scenarios throughout the source code life cycle imply significant changes in initial software architecture [9]. That is why it is of great interest to develop a universal solution for systems of different complexity, where at full change or insignificant modification of some elements there would not occur global transformations in the architecture of the whole software.

2 Architecture Development

In order to ensure the maximum efficiency of the software throughout its lifetime, it is necessary to refine it, to implement new functionality. Such actions often lead to the deterioration of the code quality and to the difficulty of reading it. One of the most successful and often used in practice approaches to solving this problem is refactoring [10]. Refactoring is a change in the inner structure of the software which is carried out in order to simplify the understanding of its work and simplify the modification without affecting the observed behavior [11]. All these modifications often lead to dramatic changes in the original software architecture. To avoid such incidents, architects initially, when designing a program, resort to multi-layer program architecture.

3 The Concept of Layers

Multilayer architecture is one of the main architectural methods of software development, in which functional areas of a program are divided into classes [12, 13]. The separation conditions are such that the functions within a group must be aimed at solving a single problem. The task of a layer strictly defines its role and responsibility.

The advantages of such a division are:

- An easy formalization of layers. It consists of the fact that layer n is a component or their set and can use only the components of layer n − 1. In turn, layer n can only be used by components of layer n + 1;
- Simple and obvious semantics. It consists in setting up a strict hierarchy of layers in the program. For example, layer n uses layer n − 1 and as a consequence, its abstraction level is higher (or at least not lower). Thus layer n − 1 allows higher abstraction levels to implement more complex concepts;
- Minimal dependency between layers. For global changes within one layer, developers only need to set up integration with the layer above;
- Wide potential for development. This approach to building software architecture can be called universal for most modern developments.

The disadvantages of such a division are:

- Cascading changes. Layers can successfully encapsulate a lot, but not everything: modifying one layer sometimes involves making cascading changes to the layers above;
- Drop in performance. The presence of redundant layers often reduces system performance.

The structure of the software, built on the principle of multilayer architecture, can be represented as a ladder, where each successive step is located on top of the previous one [14]. As part of this work, implemented a three-layer architecture of the software to build a digital model of the thermal scheme of the thermal power plant Fig. 1.

At the very top of the ladder is the abstract user interface layer. What it will look like and what technology will implement this layer is a secondary question. For example, it could be an application interface on the desktop or a page in a browser. The main task in implementing this layer is to present an ergonomic interface to the user, corresponding to the logic implemented by the layers below. It is important that the user does not feel discomfort when working, and that all functions on the window form are called simply and intuitively. In Fig. 1, the first layer refers only to block number one.

The second layer of the layered architecture is the business logic layer. In Fig. 1 this layer is represented by blocks number 2–6, where:

- Block number 2 is a block for creating a simulated thermal scheme. It implements the constructor principle. Its functionality is that it creates links between blocks

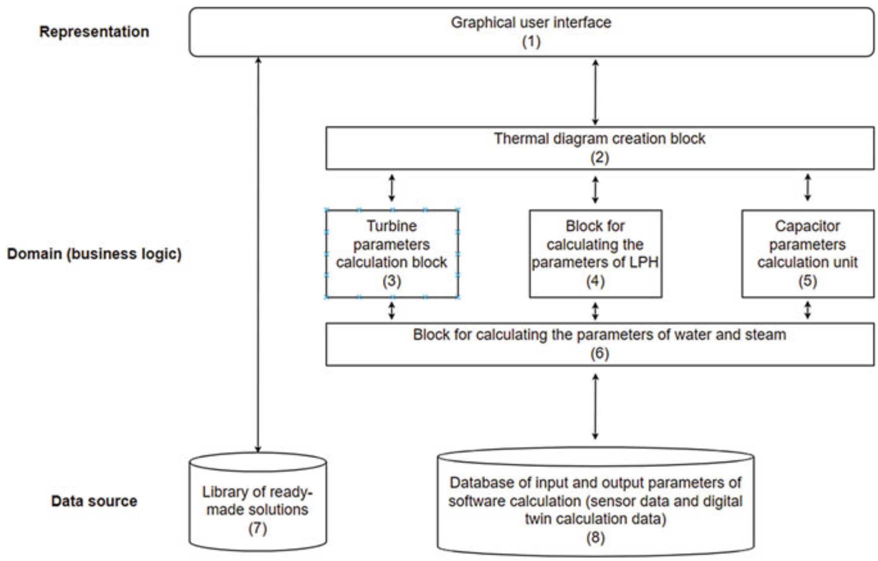

Fig. 1 Implementation of the concept of layers in the software product for building a digital model of the thermal scheme of a thermal power plant

3–5 and allows the user to simulate not a specific element of the main or auxiliary equipment, but a system, a set of elements;

- Block number 3 is a block for calculating the parameters of the heat turbine. It implements the logic, according to which the program simulates the turbine operation;
- Block number 4 is a block of calculating parameters of a low-pressure heater. Block 4—block of calculation of parameters of the low-pressure heater. It is needed to create a digital duplicate of a part of the regeneration system of the heat and power plant;
- Block number 5 is a block for the calculation of condenser parameters. It implements the logic of calculation of the condenser of the heating plant.
- Block number 6 is a block of calculation of thermodynamic parameters of water and water steam. This logic-level element is necessary for the simplification and optimization of the simulation system code. All functions of coolant dependence are placed in it, and the blocks that simulate the behavior of the main and auxiliary equipment of the TPP are addressed to it.

For example, as part of the development of the architecture of the digital twin thermal circuit of the thermal power plant has already implemented a digital model of the condenser, the fifth block [15]. Part of its logic can be seen in Fig. 2.

Figure 3 shows the results of the simulation of the condenser unit. The input data for the calculation and the results of the simulation of the condenser are displayed here.

```
tk = 30 + 273.15  # As a first approximation, we take the saturation temperature in the condenser to be 30°C
while delta > 0.1:
    r = HSST(tk) - HSWT(tk)  # Heat of vaporization
    t2в = t1в + ((Gn * r) / (Gв * 4.19))  # Condenser outlet water temperature
    delta_t = (t2в - t1в) / (log((tk - t1в) / (tk - t2в)))  # Average logarithmic temperature difference
    tcp_в = (t1в + t2в) / 2  # Average water temperature in pipes
    tn = (tk + tcp_в) / 2  # Condensate film temperature

    # by the temperature of the condensate film we determine it's:

    # Thermal conductivity
    lambda_n =1.6630 * (tn/300)**(-1.15)-1.7781*(tn/300)**(-3.4)+1.1567*(tn/300)**(-6.0)-0.432116*(tn/300)**(-7.6)
    # Condensate film density
    po_n = DSWT(tn)
    # Dynamic viscosity
    mu_n = (1.78 * 10 ** (-6)) / (1 + 0.0337 * (tn - 273.15) + 0.00021 * (tn - 273.15) ** 2) * DSWT(tn)
    # Heat of vaporization
    delta_h_n = HSST(tn) - HSWT(tn)
    # Heat transfer coefficient for condensation of practically stationary steam on horizontal smooth tubes
    alfa_n = 0.728 * (
            delta_h_n * 1000 * lambda_n ** 3 * po_n ** 2 * 9.81 / (mu_n * (tk - tcp_в) * dн * 10 ** (-3))) ** 0.25

    # by the average temperature of the water in the pipes we determine it's properties:

    # Kinematic viscosity
    nu_в = (1.78 * 10 ** (-6)) / (1 + 0.0337 * (tcp_в - 273.15) + 0.00021 * (tcp_в - 273.15) ** 2)
    # Thermal conductivity
    lambda_в =1.6630 * (tn/300)**(-1.15)-1.7781*(tn/300)**(-3.4)+1.1567*(tn/300)**(-6.0)-0.432116*(tn/300)**(-7.6)
    # Prandtl number
    Pr = 10.928 * e ** (-0.032 * (tcp_в - 273.15)) + 1.212
    # Water density
    po_в = DSWT(tcp_в)
```

Fig. 2 Code fragment of capacitor digital twin

```
Input parameters of the digital capacitor model:

Enter the steam flow rate to the condenser, kg/s: 319.6
Enter the cooling water flow rate, kg/s: 15700
Enter the condenser inlet water temperature, K: 288.15
Enter the outer diameter of the tubes, mm: 28
Enter the inner diameter of the tubes, mm: 26
Enter the number of water strokes: 2
Enter the velocity of water in the tubes, m/s: 2.1
Enter the heat exchange surface area, m2: 36138
Enter the number of tubes, pcs: 24296

Program output:

Water temperature at the condenser outlet: 26.818°C
The value of the saturation temperature in the condenser: 28.923°C
Saturation pressure in the condenser: 3.991kPa
```

Fig. 3 Input data for capacitor simulation and calculation results

Below is the data source layer. This layer is the source layer. It also describes the logic, which provides interaction with the source and the transfer of the results to the layer above. In Fig. 1 this abstract layer is represented by blocks number 7 and 8, where:

- Block number 7 is a library of ready-made solutions. This database contains thermal schemes, which are ready for modeling, that were modeled earlier;

- Block number 8 is a database of input and output parameters of the program calculation. This database stores the history of simulation of the heat scheme elements, as well as the data from the physical sensors of the I&C system.

As can be seen from the description of the schema in Fig. 1, all layers and even the functionality of the blocks are aimed at solving one specific task and do not overlap with the rest.

There may be other layers in the layer concept as well, and the sequence of their arrangement depends on the specific product. Next, let's consider the bottom layer of the layered architecture—the abstract data source layer.

4 Data Source

Database design consists of two fundamental phases: logical and physical modeling [16].

In the process of logical modeling, the architect develops a database model that does not depend on a particular database management system (DBMS) [17]. This stage can be divided into the following stages:

- Gathering requirements;
- Definition of entities;
- Definition of attributes for each entity:
- Definition of relationships between entities;
- Normalization.

During the requirements gathering phase, the architect needs to determine exactly what information will be stored in the database and how it will be used. Here, a decision must be made about the capabilities of the DBMS and the functions it should be able to perform.

In the entity definition phase, the architect needs to decide what entities the database should consist of. An entity is an object in the database in which records are stored. Entities, in particular, are tables. The number of tables should be minimal, but exhaustive. This condition must be met with maximum precision because the DBMS query execution speed depends on it.

At the attribute definition stage, the architect must decide which attributes (columns) will describe this or that entity. For each attribute, it is important to determine the data type and size, allowable values, and many other rules. For example, mandatory filling, keys (primary and external), indexing, logging by query execution time, query termination by timeout, and much more.

At the entity-relationship definition stage, the architect needs to determine how the various tables will be related to each other. An entity-relationship is a situation where one table refers to the primary key of another table. Here it is important to identify all possible logical relationships that exist between the tables. Entity relationships are divided into three types: one-to-one, one-to-many, and many-to-many. When constructing entities, the architect should try to avoid many-to-many relationships.

During the normalization phase, the architect must detect and remove all redundant data from the database [18]. Each data item must be stored in one and only one instance. There are five common forms of normalization. Typically, the database is reduced to the third normal form (the third normal form excludes attributes that do not depend on the key). In the standardization process, some steps are taken to remove redundant data. Normalization improves performance, speeds up sorting and index construction, reduces the number of indexes per unit, and speeds up insertion and updating. A standardized database is usually more flexible. When you change queries or data stored in a normalized database, you usually have to make fewer changes and make changes that have fewer consequences.

Figure 4 shows an ER—diagram for the database [19] represented by block number 8 in Fig. 1. An ER—diagram is a kind of block diagram that shows related entities. We can say that the result of the third normal form is the construction of the entity-relationship diagram. This diagram contains 11 tables linked one-to-one, where:

- digital_twin_db.turbine_in—table of input parameters for turbine verification calculation (data from sensors);
- digital_twin_db.LPH_in—table of input parameters for LPH verification calculation (sensor data);
- digital_twin_db.capacitor_in—table of input parameters for capacitor verification calculation (data from sensors);
- digital_twin_db.t_expansion_out—table with the output data of the calculation of the process of expansion of the flow part;
- digital_twin_db.t_ei_out—table with output data of turbine power calculation;
- digital_twin_db.t_ad_out—table with output data for calculating axial movements of the turbine unit rotor and casing;
- digital_twin_db.t_log—turbine critical faults logging table;
- digital_twin_db.LPH_out—table with the output data of the LPH verification calculation;
- digital_twin_db.LPH_log—table for logging critical LPH faults;
- digital_twin_db.capacitor_out—table with the output data of the verification calculation of the capacitor;
- digital_twin_db.capacitor_log—table for logging critical capacitor faults.

This ER diagram uses three types of data: numeric, timestamp, varchar. These formats were chosen because of the consideration of the greatest speed of processing queries to the database. As the SQL language works fastest with the numeric data type, then timestamp and varchar.

Having a logging table will be an indispensable tool in the process of creating and maintaining an application. When searching for errors in the code and localizing system defects. When software behaves incorrectly at runtime and the reason for such behavior needs to be identified within a short period of time. In other words, the

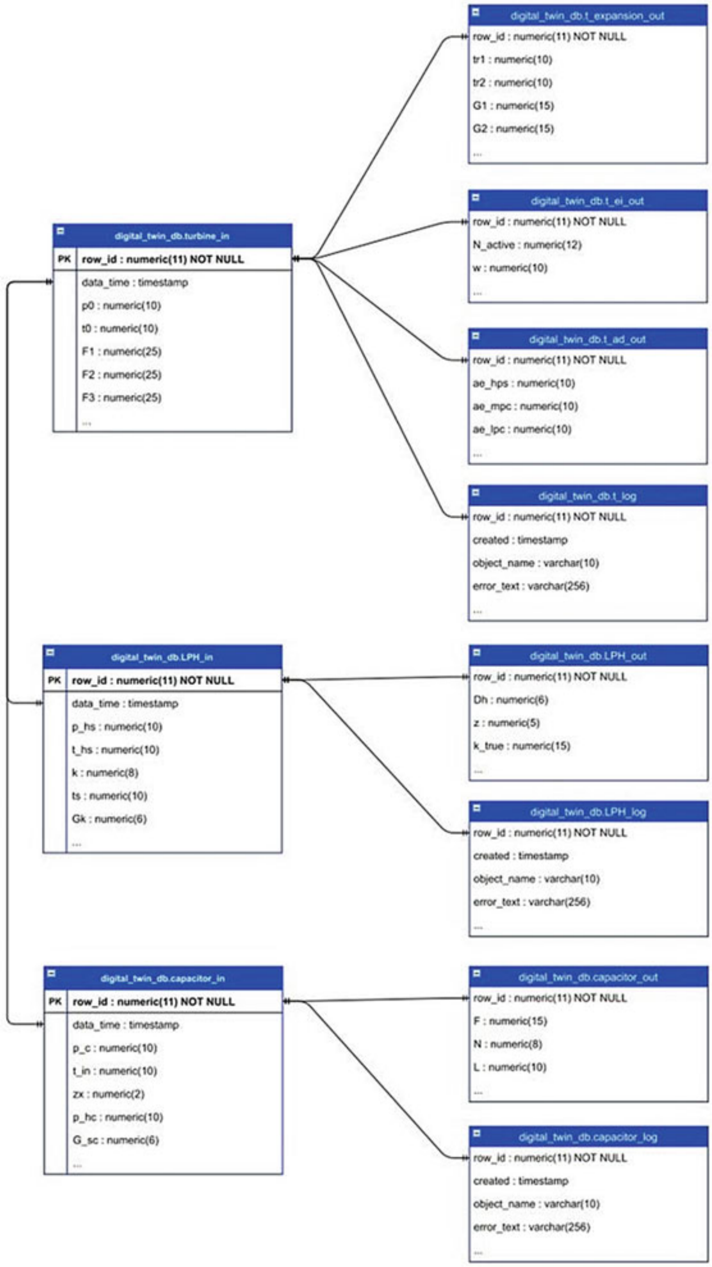

Fig. 4 ER—diagram

implementation of a critical error logging table will greatly reduce the time needed to find and localize defects in the system (time for analysis).

In the physical modeling process, the developer creates a model optimized for the specific application and DBMS. It is this model that is implemented in practice. This stage can be divided into the following stages [20]:

- Conversion to a physical model;
- Creating a database.

At the stage of physical model transformation and database creation, the specifics of a particular data model and the specifics of a particular DBMS are taken into account. Entities identified at the logical data model formation stage are converted into tables, attributes become columns, unique indexes are created for key attributes, and domains are converted to the data types accepted by the used DBMS. Constraints in the logical data model are implemented by various DBMS tools, e.g., with the help of indexes, integrity constraints, triggers, stored procedures. At the same time, the decisions made at the logical modeling level determine the specified limits within which a physical data model can be developed. Similarly, different decisions can be made within these limits. For example, relationships in a logical data model must be converted into tables, but different indexes can additionally be declared for each table to increase the rate of data access. It all depends on the particular DBMS.

The physical design of the database also includes selecting an efficient location of the database on an external medium to ensure the most efficient operation of the program.

The physical modeling phase evaluates the computer resource requirements needed to run the entire system, selects the type and configuration of the server, the type, and the version of the operating system.

5 Conclusion

In this chapter one of the possible approaches to software architecture implementation—multilayer architecture—has been considered. Each abstract layer is characterized, the advantages and disadvantages of this method are described. Using this approach, a software architecture was developed to build a digital model of a thermal scheme of a thermal power plant. Also, one of the layers of multilayer architecture was realized—the data source. An ER diagram of the digital modeling subsystem was built.

The implementation of software architecture is one of the most important stages of the life cycle. It is from this stage that the further fate of the developed product will depend. And how much money was spent on the organization of the software system will depend on the duration of its life cycle, ease of use, and maintenance.

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Society 5.0: Advances in Transport Systems

Secondary Pollution of the Urban Atmosphere by Motor Transport at Various Emission Capacities

Vadim A. Zaytsev

Abstract Air pollution in the area of influence of the highway is considered. To find the capacities of primary pollutants emissions during this task, an appropriate methodology for assessing the impact on the environment is used, then, to determine their concentrations, the dispersion is calculated under unfavorable meteorological conditions. For the secondary pollutant—ozone—the concentration calculations are performed using the proposed mathematical model. It is based on a stiff system of differential equations describing the kinetics of this process and solved by the Rosenbrock method. The initial conditions are the arithmetic mean values of the concentrations of primary pollutants obtained at the previous step. A possible increase in the ozone content is investigated with a change in the intensity of the traffic flow, as well as in different wind directions. The possibility of formation on the leeward side of the highway of a rather wide area of its influence, characterized by high concentrations of secondary and primary pollutants, is analyzed.

Keywords Mathematical modeling · Systems of stiff differential equations · Environmental impact assessment · Environmental chemistry · Atmospheric chemistry · Chemical kinetics · Ecology

1 Introduction

Mathematical modeling is quite often used in the study of atmospheric pollution along with direct measurements of the concentrations of pollutants. As the problem is studied, new reactions are added to the chemically active systems under consideration, which makes it possible to obtain more accurate results [1, 2].

In some works devoted to the atmosphere of Moscow, experimental data on primary pollutants obtained at environmental monitoring stations are used to assess

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the content of a more toxic secondary pollutant, ozone, in the air [3–8]. The chemical transformation process is considered under cramped aerodynamic conditions. These are city highways, bordered by rows of tall and wide buildings. Due to the hindered dispersion in these areas, sufficiently high concentrations of compounds of the above-mentioned first group are created. This circumstance contributes to the intensive course of chemical reactions in this zone, and as a consequence of this, the quantitative synthesis of O_3 has time to occur before the substances leave it. Various variations in the concentration of primary pollutants are considered, and conditions are being sought to achieve the maximum value of the ozone concentration. These publications touch upon areas in which sufficiently high local concentrations of substances are created and the scales of distances are relatively small. As a rule, problems in cramped hydrodynamic conditions for other cases have been studied in less detail [9].

Other articles [10–12], in contrast to them, are characterized by the use of large distances. The publication [10] is devoted to calculations of atmospheric pollution in Moscow and several neighboring regions. The model is tested for adequacy by comparing the calculated and measured surface concentrations of nitrogen dioxide and ozone. Some modeling works are the results of joint calculations using meteorological and chemical transport models [11, 12].

However, a distinctive feature of all the above works is the presence of studies on tropospheric ozone. This is due to its negative impact on the human respiratory and cardiovascular systems, which entails an increase in mortality. A large number of articles are devoted to the study of these issues [13–18].

Since secondary air pollution with ozone contributes to an increase in air toxicity, reviews on this topic are regularly published, in which the publications of many authors are considered [19–21].

It should be noted that for carrying out model studies, the values of the rate constants of many atmospheric reactions are required. Some of them are contained in works [22–26]. Because of the importance of the above-mentioned problem of secondary air pollution, these data on the rate constants are regularly updated by adding new reactions and refined [27–29].

The article [30] is devoted to the study of the distribution areas of carbon monoxide on the road section. To calculate the emission power of vehicles, it used the methodology [31].

2 Research Problem Statement and Scientific Novelty

In publications [3–8], variations in the concentration of primary pollutants upward compared to the base case are investigated, which is quite likely with an increase in the flow of cars. However, the number of the latter was not estimated in it. In [30], based on this value, the propagation of only one substance without any chemical transformations is studied in detail. Therefore, the purpose of this chapter was to relate the number of transport units on the highway, the emission power of each primary pollutant, their concentration resulting from dispersion, and ozone formed during the process of chemical transformation of these compounds. In an attempt to link, ultimately, the first and last indicators of this sequence lie in scientific novelty. In addition, the task is set so that numerical experiments are carried out at distances from the highway that are important for assessing its impact, however, where there is a relatively small change in the concentrations of primary pollutants, i.e. they are considered constant, equal to their arithmetic mean values. This allows one to consider independently the transfer and chemical transformation. Due to this, at the last stage, a system of ordinary differential equations is solved, instead of a system of partial differential equations. And this makes it possible to save computational resources for a significant increase in the number of differential equations with the further inclusion in the model in the future of a significant number of new substances that will become significant for this problem under different conditions. The errors of the solution will also be lower.

This approach makes it possible to predict secondary air pollution with significant road filling, which can occur under the worst dispersion conditions. One of them is low wind speed or its complete absence. The ability to carry out such assessments based on the intensity of the flow of cars is also interesting because this value is subject to change not only in environmental problems. Thus, the article [32] discusses the management of traffic flows in intelligent transport systems to improve the efficiency of transportation.

3 Proposed Mathematical Model and Numerical Experiments

The calculation of emissions from moving vehicles was carried out according to the formula (1). It is proposed in the methodology [31]:

$$M_{L_i} = \frac{L}{1200} \cdot \sum_{1}^{k} M_{k,i}^{L} \cdot G_k \cdot r_{V_{k,i}}, \tag{1}$$

where M_{L_i} is the power of emission of the i-th pollutant by a stream of cars, g/s; $M_{k,i}^{L}$—the normative value of the emission of the i-th pollutant by vehicles of the k-th type is taken from Table 1, g/km; k is the number of types of machines; G_k—the present maximum traffic density, i.e. the number of cars of each of k types crossing a given section of the highway in 20 min in two directions and on all its lanes; $r_{V_{k,i}}$—the correction factor for the average speed of the flow of cars ($V_{k,i}$, km/h) is taken from Table 2; L is the length of the investigated part of the road, on which there should be no traffic lights (for them, the calculation is carried out differently), km.

The object of the study was a 1 km section of the city highway, on which the movement of trucks is prohibited. The stream consists of passenger cars, as well as

Table 1 The normative value of the emission of the *i*-th pollutant by the vehicles of the *k*-type $M^L_{k,i}$, g/km [31]

Number and name of the car group	The normative value of the emission, g/km						
	CO	NO_x (in terms of NO_2)	CH	Soot	SO_2	Formaldehyde	Benz (a) pyrene
Passenger cars	3.5	0.9	0.8	$0.7 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	$3.2 \cdot 10^{-3}$	$0.3 \cdot 10^{-6}$
Vans and minibuses weighing up to 3.5 t	8.4	2.1	2.4	$3.8 \cdot 10^{-2}$	$2.8 \cdot 10^{-2}$	$8.4 \cdot 10^{-3}$	$0.8 \cdot 10^{-6}$
Freight weighing from 3.5 to 12 t	6.8	6.9	5.2	0.4	$5.1 \cdot 10^{-2}$	$2.2 \cdot 10^{-2}$	$2.1 \cdot 10^{-6}$
Freight weighing over 12 t	7.3	8.5	6.5	0.5	$7.3 \cdot 10^{-2}$	$2.5 \cdot 10^{-2}$	$2.6 \cdot 10^{-6}$
Buses weighing over 3.5 t	5.2	6.1	4.5	0.3	$4.2 \cdot 10^{-2}$	$1.8 \cdot 10^{-2}$	$1.8 \cdot 10^{-6}$

Table 2 Correction factor for the average flow rate of machines $r_{Vk,i}$ [31]

	The average flow rate of cars, *V*, km/h														
V	5	10	15	20	25	30	35	40	45	50	60	70	80	100	110
$r_{Vk,i}$	1.4	1.35	1.3	1.2	1.1	1.0	0.9	0.75	0.65	0.5	0.3	0.4	0.5	0.6	0.75
$r_{Vk,i}(NO_x)$	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.2

vans and minibusses, accounting for 5% of the total number of vehicles. The road contains three lanes in both directions. Setting the average values of the length of cars, the distances between them (4 options: 30, 50, 100, and 200 m), their speeds (60 km/h), and assuming the uniformity of these values in all its lanes, it is possible to calculate the number of cars crossing a given section of the highway in 20 min in forward and backward directions.

Based on this, according to formula (1), the emission rates of the primary pollutants were calculated: nitrogen monoxide and nitrogen dioxide, carbon monoxide, methane, and formaldehyde. It should be noted that for NO and NO_2, these values were also determined taking into account the transformation coefficient of nitrogen oxides in the atmosphere, which is typical for air near highways, and CH_4 was considered to be the dominant hydrocarbon in the emissions of the considered groups of cars.

Then, using a standard certified program, the dispersion was calculated. In this case, a wind speed of 1 m/s was considered (such small values are the most unfavorable) and a direction perpendicular to the road, which is an areal source of emissions. The origin of coordinates is located in its middle, therefore, the concentrations

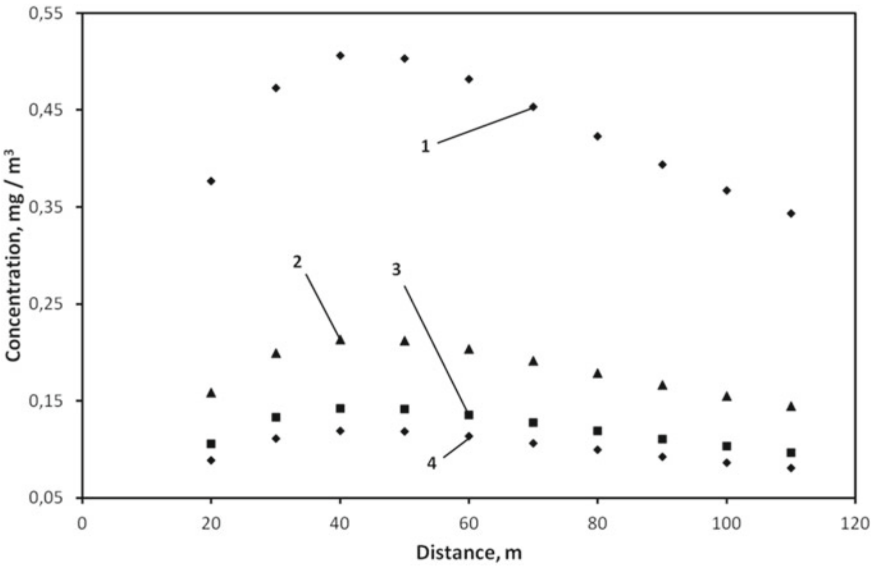

Fig. 1 Dependence of the concentration of the emitted substance on the distance from the highway for the direction of the wind perpendicular to it, with an average distance between cars of 50 m: 1 – CO; 2 – NO_2; 3 – NO; 4 – CH_4

calculated outside this rectangle are considered reliable, i.e. starting from 20 m. The dependences of the concentrations of emitted substances on the distance from the motorway for an average distance between cars of 50 m are shown in Fig. 1.

Their arithmetic mean values for each substance, in the same order, respectively, are equal to 0.432; 0.182; 0.121; 0.102 mg / m^3. Due to the very low air content, formaldehyde is not shown in this graph. However, the nature of the dependence for it is the same, and the average concentration is $3.99 \cdot 10^{-3}$ mg/ m^3.

Since for all cases the geometric parameters of the source remain unchanged, we can talk about the similarity of the concentration fields. Thus, they will change in direct proportion to the corresponding emission rates, i.e. for distances between cars 30; 100 and 200 m must be multiplied by 1.59; 0.521 and 0.265, respectively.

The difference between the maximum concentration values and the arithmetic mean for each substance is about 17%, and the minimum—20%. Therefore, as an assumption, they are considered unchanged, equal to these average values, up to a distance of 110 m. Further, they are used, taking into account the background values, in the form of initial concentrations when solving a system of differential equations describing the chemical transformation of these substances in the atmosphere. Its compilation is considered in detail in [3–8], and in this work, for a more convenient perception, only the main points are noted.

As noted earlier, to carry out model studies, the values of the rate constants of many atmospheric reactions are required. They act as initial data in this work and are contained in articles [27, 28].

Table 3 Chemical reactions that need to be considered in a mathematical model and the corresponding rate constants [2–8, 27, 28]

Reaction number	Chemical reaction	Rate constant
1	$CH_4 + HO^\bullet \rightarrow {}^\bullet CH_3 + H_2O$	$k_1 = 7{,}9 \cdot 10^{-15}$
2	${}^\bullet CH_3 + O_2 + M \rightarrow CH_3O_2{}^\bullet + M^*$	$k_2\ [M] = 1{,}8 \cdot 10^{-12}$
3	$CH_3O_2{}^\bullet + NO \rightarrow CH_3O^\bullet + NO_2$	$k_3 = 7{,}6 \cdot 10^{-12}$
4	$CH_3O^\bullet + O_2 \rightarrow CH_2=O + HO_2{}^\bullet$	$k_4 = 1{,}3 \cdot 10^{-15}$
5	$CH_2=O + h\nu \rightarrow {}^\bullet CH=O + H^\bullet$	$k_5 = 3{,}7 \cdot 10^{-5}$
6	$CH_2=O + h\nu \rightarrow CO + H_2$	$k_6 = 4{,}9 \cdot 10^{-5}$
7	$CH_2=O + HO^\bullet \rightarrow {}^\bullet CH=O + H_2O$	$k_7 = 1{,}0 \cdot 10^{-11}$
8	${}^\bullet CH=O + O_2 \rightarrow CO + HO_2{}^\bullet$	$k_8 = 5{,}5 \cdot 10^{-12}$
9	$CO + HO^\bullet \rightarrow CO_2 + H^\bullet$	$k_9 = 3{,}0 \cdot 10^{-13}$
10	$H^\bullet + O_2 + M \rightarrow HO_2{}^\bullet + M^*$	$k_{10}\ [M] = 1{,}4 \cdot 10^{-12}$
11	$HO_2{}^\bullet + NO \rightarrow NO_2 + HO^\bullet$	$k_{11} = 8{,}3 \cdot 10^{-12}$
12	$NO_2 + h\nu \rightarrow NO + O(^3P)$	$k_{12} = 8{,}9 \cdot 10^{-3}$
13	$O(^3P) + O_2 + M \rightarrow O_3 + M^*$	$k_{13}\ [M] = 1{,}8 \cdot 10^{-14}$
14	$O_3 + NO \rightarrow NO_2 + O_2$	$k_{14} = 1{,}8 \cdot 10^{-14}$

The chemical reactions that must be considered under these conditions and the corresponding rate constants are given in Table 3 [2–8, 27, 28].

On their basis, using the law of mass action, it is possible to calculate the total rates of formation F_i and sink R_i of each of the reacting substances. The time variation of the concentration of any starting substance and the product of these reactions can be calculated using equations of the type (2):

$$\frac{dC_i}{d\tau} = F_i - R_i \tag{2}$$

The result is a rigid system consisting of 17 differential equations. To solve such a system, to avoid the loss of its stability, it is necessary to use special methods. In this work, we used the Rosenbrock method [3–8].

The results of numerical experiments for secondary pollution of the atmosphere at a distance of up to 100 m from the leeward side of the highway are shown in Fig. 2.

It is assumed that at the considered wind speed, substances will reach this boundary in 100 s.

As follows from the figure, the road makes a significant contribution to the increase in the O_3 content. This effect increases with increasing traffic intensity. At the same time, it was assumed that from the windward side, air with an O_3 content corresponding to the average daily maximum permissible concentration of 0.03 mg/m^3 is supplied to the highway.

Buildings, especially wide buildings of great height, located in a similar area of influence of the highway, prevent the dispersion of primary pollutants, which leads

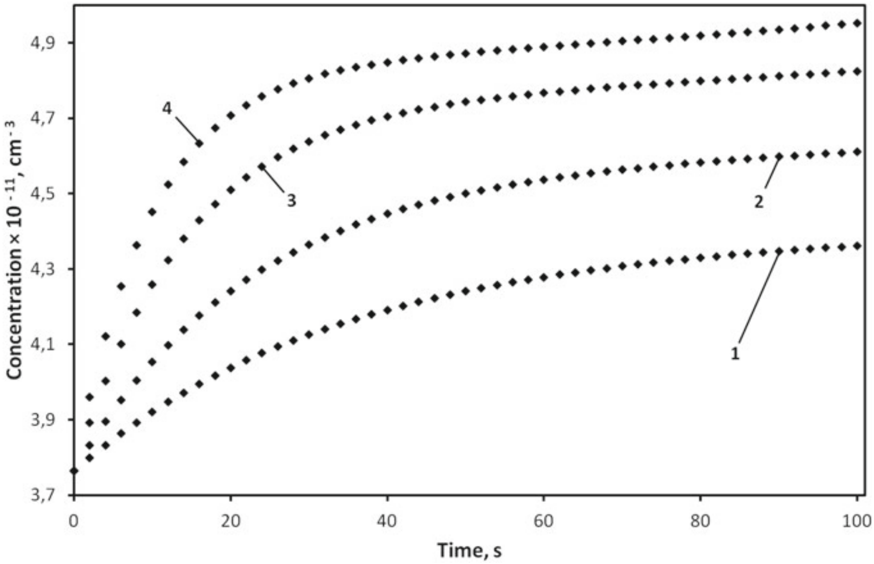

Fig. 2 Change in ozone concentration over time for the direction of the wind perpendicular to the highway, at different intensities transport stream, determined by the average distance between cars: 1–200 m; 2–100 m; 3–50 m; 4–30 m

to an even greater increase in their concentration and, as a consequence, to an even greater secondary pollution.

Of course, the wind can be directed not only perpendicular to the road. Therefore, consider the case when it blows at an angle of 45°. The corresponding dependences of the concentrations of emitted substances on the distance from the highway for an average distance between cars of 50 m are shown in Fig. 3.

It should be noted that in areas where aerodynamic stabilization has already taken place, at distances of about 100 m long and 100 m across the road, the concentration isolines are practically parallel to it. Therefore, this graph, for convenience of comparison with Fig. 1 shows the concentration projections on the axis perpendicular to the highway. In this case, the actual movement of air is carried out along the hypotenuse of an isosceles right-angled triangle. Thus, these projections must be multiplied by $\sqrt{2}$ to calculate the actual travel distances. Then the considered time, during which the synthesis of ozone occurs, must be increased by the same number of times. That is, at a wind speed of 1 m/s, to compare the results, instead of a time of 100 s, approximately 141 s are taken. These dependencies are shown in Fig. 4.

Comparison of the corresponding results shows that when the wind is directed at an angle of 45° to the road, in comparison with the perpendicular one, the average concentration of primary pollutants increases by more than 26%. Whereas the content of the secondary pollutant—ozone—does not increase so significantly, by almost 3%.

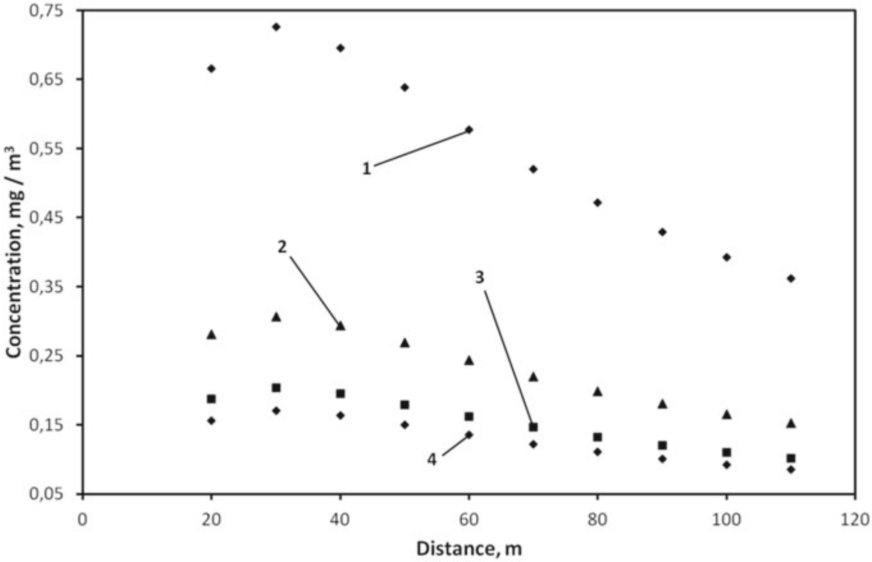

Fig. 3 Dependence of the concentration of the emitted substance on the distance from the highway for the wind direction at an angle of 45° to it, with an average distance between cars of 50 m: 1—CO; 2—NO_2; 3—NO; 4—CH_4

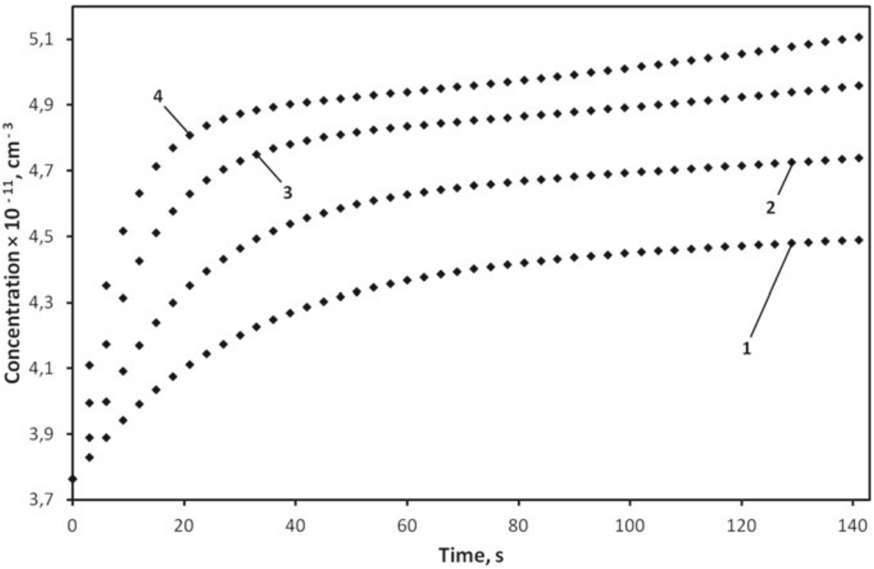

Fig. 4 Change in ozone concentration over time for wind direction at an angle of 45° to the highway, at different intensities transport stream, determined by the average distance between cars: 1–200 m; 2–100 m; 3–50 m; 4–30 m

4 Conclusions

At a low wind speed and an intense flow of cars from the leeward side of the highway, a fairly wide area of its influence is formed, characterized by high concentrations of primary pollutants.

During the time of transfer to its border, during the process of their chemical transformation, there is a quantitative increase in the concentration of a more toxic secondary pollutant—ozone.

If air with an O_3 content corresponding to the average daily maximum permissible concentration approaches the motorway from the windward side, then in the worst case, its increase from this value by about a third is observed. But there is no excess of the maximum one-time maximum permissible concentration, a comparison with which in these circumstances is more correct.

The presence of wide buildings of great height, preventing the dispersion of substances, enhances the above-mentioned negative effects.

When the wind direction changes from perpendicular to 45° at an angle to the highway, the intensity of secondary pollution does not increase as much as the primary one.

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The Intellectual Transport with Divisible Parts

E. V. Shviatsova and V. N. Shuts

Abstract The main disadvantages of modern urban passenger transport are considered and ways of eliminating them through the introduction of intelligent transport systems based on unmanned vehicles that can move in automatic mode and to have the ability to split into two independent unmanned autonomous vehicles before the stopping point are considered. When a vehicle with divisible parts passes through a stopping point, its end part, in which passengers need this stop is collected, separates, and stops on the point while the front part moves further. This principle of organizing the movement of passenger vehicles provides more rational use of time and kinetic energy are spent on accelerating and braking the vehicle at a stop in comparison with the traditional approach, when the entire vehicle both with passengers leaving the vehicle at this stop, and with passengers who do not need this stop, brakes. This solution improves efficiency and reduces the energy consumption of this type of transport.

Keywords Passenger transport · Intelligent transport · Smart transport · Information transport system · Transport with divided parts · Smart urban mobility · Intelligent transport system

1 Introduction

Motor transport represents one of the largest branches of the national economy with a complex and diverse equipment, as well as the specific organization and system of management. Urban bus transportation is subsidized from the budget, therefore, it is necessary to increase self-sufficiency and, accordingly, reduce the size of subsidies for public transportation of passengers. The transportation enterprises have the task of optimizing transportation activities and equality of demand for transportation and

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the supply, with minimum transport costs. There is a permanent need to improve the quality of passenger services. An increase in the quality of passenger services and, at the same time, a reduction in the cost of their organization can be achieved by operatively regulating the motion of rolling stock along the routes.

The main task of the organization of the city transport movement is to ensure the highest quality of passenger transportation with a minimum cost. The quality of passenger transportation is estimated by the regularity of transport traffic, the size of the route interval, the filling of buses, the time spent by the population on journeys, the speed of communication, and the comfort of transport service [1–3]. An increase in the quality of transport services results in increases in the cost of passenger transportation. Therefore, the requirement to increase the quality indicators of passenger transportation and minimize their cost is contradictory. If the unregulated random fluctuations of passenger traffic flow in time and along the length of the transport network are accounted, the inevitable delays of the route passenger transport when working in the general traffic flow, etc., it becomes obvious that the composition of the optimal traffic plan is a very complex task.

The traffic plan, on the one hand, should be quite intense, i.e. it should be designed for the maximum output of the rolling stock on the line, the maximum useful use of the duration of the working time of transport employment, the realization of the maximum speed, etc. All these factors will carry out reducing the cost and improve the quality of passenger transportation. However, on the other hand, traffic plan must have sufficient reserves of rolling stock for possible changes vehicles on the traffic line in case of delays due to possible incidents, in terms of movement speed, taking into account the need for overrun time reserves in case of various traffic disruptions, etc.

Thus, at present, the main way to improve the efficiency of passenger traffic is the optimization of the urban route network, optimization of vehicle intervals at different periods of the day depending on passenger traffic. However, this is not enough. It is still necessary to have vehicles with completely new features and capabilities [4–15].

2 The Ratio of Useful and Total Vehicle Weight and Their Impact on Passenger Transportation Efficiency

As noted above, optimizing the route network and vehicle schedule alone is clearly not enough. Large economic losses are incurred by vehicles at stops and acceleration from stop points.

Let's consider a bus (trolleybus, tram) route consisting of 12 stopping points in one direction. For example, the passenger rides from the starting point to the final point with 10 intermediate stops that are needn't by him. Let's that at each intermediate stop 0.1 of the vehicle's passengers will leave the bus and new ones will be loaded into. Thus, at each stop, the kinetic energy proportional to 0.9 of the masses of passengers who do not need to leave at that stop is uselessly extinguished. The kinetic energy corresponding to the mass of the vehicle is also lost.

Let's perform some calculations under the following assumptions. Thus, the average mass of the passenger will be 71 kg. Passenger density in the vehicle cabin will be 5 persons/m^2. Hence for a large class of buses (MAZ-103), which has dimensions, mm: 11,985/2500/2838; weight, kg: 18,000; nominal capacity (5 persons/m^2): 90, will be the following indicators:

$90 \times 71 = 6390$ (kg)—Useful weight
$90 \times 71 + 18000 = 24390$ (kg)—Full weight
$6390 \div 24390 = 26.2\%$ (kg)—Ratio useful weight to full weight

The last value can also be considered as the coefficient of efficiency of a passenger vehicle. Consequently, $100\% - 26.2\% = 73.8\%$ of the kinetic energy stored is wasted when braking at stopping points.

Similarly for the middle class MAZ-206, which has dimensions, mm: 8650/2550/2930; weight, kg: 13,200; nominal capacity (5 persons/m^2):72, will:

$72 \times 71 = 5112$ (kg)—Useful weight
$72 \times 71 + 13200 = 18312$ (kg)—Full weight
$5112 \div 18312 = 27.9\%$ (kg)—Ratio useful weight to full weight

Similar for small class MAZ-241, which has dimensions, mm. 6800/2550/2785, weight 8775 kg, nominal capacity (5 persons/m^2):36, will:

$36 \times 71 = 2556$ (kg)—Useful weight
$36 \times 71 + 8775 = 11331$ (kg)—Full weight
$2556 \div 11331 = 22.5\%$ (kg)—Ratio useful weight to full weight

The obtained results of the useful mass to full mass relations are summarized in Table 1. From Table 1 we can see that the efficiency coefficient of the stopping process for all types of buses is approximately the same and varies around 25%. This coefficient will be much lower in the case of subtracting 0.9 of the mass of passengers who do not have to leave at the stop were to be subtracted from the useful mass. Let's recalculate the ratio of the useful mass (0.1 of the gross vehicle mass) to the full vehicle mass with a fully filled compartment for all bus types:

Table 1 Buses

Type	Length, m	Weight, kg	Useful weight, kg	Full weight, kg	Rate useful to full weight, %
Small, MAZ-241	Over 6.0 up 7.5	8775	2556	11,331	22.5
Middle, MAZ-206	Over 8.0 up 10.0	13,200	5112	18,312	27.9
Large, MAZ-103	Over 10.5 up 12.0	18,000	6390	24,390	26.2

Big buses—639 ÷ 24390 = 2.62%
Middle buses—511.2 ÷ 18312 = 2.79%
Small buses—255.6 ÷ 11331 = 2.25%

Thus, a significant amount of kinetic energy is lost at stopping points, and therefore fuel overruns and the efficiency of passenger transportation are reduced. A way out of this situation may be to create an unmanned vehicle that can divide into two parts. One part (rear) is occupied by passengers who have to get off at another stop. When passing this stop, the rear part of the vehicle shall be separated from the front part of the vehicle and braked at the stopping point. Passengers whose destination is further than the current stop will pass this stopping point at the front of the vehicle without stopping. Thus, 0.9 of the passenger masses are in transit.

To calculate the fuel loss at one stop of the vehicle, let us denote through the MVhc vehicle's mass and the MPass—the passenger mass of a fully filled vehicle's salon. Vehicle speed when approaching the stopping point is V = 30 km/h (8 m/s). The total kinetic energy of the vehicle when approaching a stop, and which will be extinguished by braking, is equal:

$$W_1 = \frac{M_{Vhc} \cdot V^2}{2} + \frac{M_{Pass} \cdot V^2}{2}. \tag{1}$$

In the case of separation of the rear of the vehicle from the front with 0.1th of the passengers, its kinetic energy will be:

$$W_2 = \frac{0.5 \cdot M_{Vhc} \cdot V^2}{2} + \frac{0.1 \cdot M_{Pass} \cdot V^2}{2}. \tag{2}$$

It's a forced loss even when parts are separated. Let's subtract from (1) expression (2) and obtain a value (3) of the energy saved in the case of the separation system:

$$W_1 - W_2 = \frac{0.5 \cdot M_{Vhc} \cdot V^2}{2} + \frac{0.9 \cdot M_{Pass} \cdot V^2}{2} \tag{3}$$

Let's calculate the amount of lost fuel equivalent to extinguished energy (3) when stopping at a speed of $V = 30$ km/h and up to $V = 0$ for a large class of vehicle (MAZ-103) with a mass of $M_{Vhc} = 18{,}000$ kg and a full passenger compartment of $M_{Pass} = 6390$ kg:

$$\begin{aligned} W_1 - W_2 &= \frac{0.5 \cdot M_{Vhc} \cdot V^2}{2} + \frac{0.9 \cdot M_{Pass} \cdot V^2}{2} \\ &= \frac{0.5 \cdot 18000 \cdot 8 \cdot 8}{2} + \frac{0.9 \cdot 6390 \cdot 8 \cdot 8}{2} \\ &= 0.472MJ \end{aligned}$$

The amount of fuel that is used to create such an amount of kinetic energy can be found by dividing the amount of energy on the specific heat of fuel (gasoline) combustion. The specific heat of gasoline combustion is 47 MJ/Kg. So, the amount of lost fuel is 0.472/47 = 0.01 (Kg). Since the efficiency of the internal combustion engine is 25%, the fuel will be needed four times more, namely, 0.04 kg or 0.06 l.

Thus, the losses are significant, and the division of the vehicle will eliminate them. On a closed city route consisting of 11 stops (initial and final coincide), there will be 10 such separations and, therefore, fuel-saving will be 0.6 L. If we accept that the route takes 0.5 h, then during the daily work (18 h) 36 flights will be performed and $0.6 \times 36 = 21.6$ liters of fuel will be saved.

The given transport system functions in the total absence of management by the human and are essentially a new kind of public transport which basis on mobile (unmanned) independent electric cars. The following section describes the management of such a transport system. This transport system can be implemented on urban rail transport, therefore, in the future, the term «wagon» will be used instead of the bus.

3 Functioning of a Passenger Rail Vehicle with Separable Parts

The development of information technology gives opportunities to revise the structure and concept of management of modern urban transport systems through an introduction to using a new generation of passenger transport—intelligent vehicles. In the chapter, such an intelligent transport system is proposed for consideration. Depending on the intensity of the passenger traffic on the route (measured by sensors in automatic mode) the control computer (coordinating server of intelligent transport system) sends such a quantity of vehicles to the route so that their total volume was equal to or slightly higher than the passenger traffic. In this case, the vehicles are collected in cassettes which can consist of various quantities of units (one, two,…) depending on the passenger traffic at the current time. This approach gives the possibility quickly and inexpensively to assemble a vehicle of any capacity that is required on the route now [16–22].

The main active unit of the transport system is an unmanned wagon is mounted on rails or a rail (mono). It is fully autonomous and independent in choice of active actions. Its computer module provides control of all the functions of the car and "communication" with other wagons included in the system. Also, the intelligent passenger transport system consists of the route with stopping points, rail track on which wagons are located, each of these (1) is equipped with a computer module for traffic organization (Fig. 1).

The module consists of:

– the computer
– the radio module that is connected to the system bus to a computer2

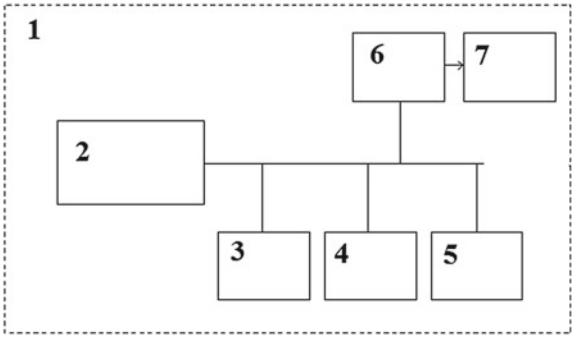

Fig. 1 Scheme of a computer module for traffic organization of unmanned wagon 1

– the block of locking incoming and outgoing passengers
– the block of locking passenger transfer between vehicles
– the control unit drive
– the control unit of vehicle motion to that input drive 6 is connected

Figure 2 shows a scheme of the transport system states that reflects the operating modes at different points in time.

For further reasoning let's assume that mode Oct.I mean that the vehicles dispose at station point, Ctk.i—the mode of vehicles docking, Pctk.i—the mode of vehicles undocking. For the convenience of consideration in Fig. 2 cars, which are at rest, are depicted without arrows, and the vehicles in of motion—with arrows.

The rolling stock of two wagons B1 and B2 (state S0(t)) starts motion from stopping point 1 (mode Oct.1). It moves with a uniform speed V and at time t2 the wagons undock (state S1(t), mode Pctk.2). Wagon B1 continues its further running at a constant speed V. It carries passengers that do not need to leave at stop 2 (Oct.2).

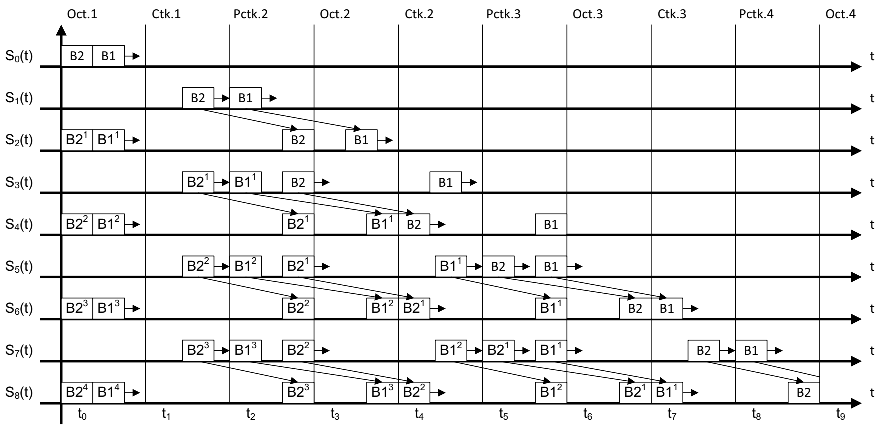

Fig. 2 The scheme of transport system's states

The passengers who need to stop 2 are in the second car B2, which at the moment t3 stops on Oct.2. This event corresponds to the state S2(t).

At the moment of stopping of the second car B2 on Oct.2, the following train B21B11 leaves from stop 1 (Oct.1). It also at the moment t2 disconnects (S3(t)). The first B11 car continues to run uniformly at the same speed V. The B21 car stops on Oct.2, moving evenly and slowly. The car B2 that before this time was standing at the stopping point Oct.2 leaves this stop. The departure of car B2 from the stop on Oct.2 begins at the moment of unbinding the tandem B21B11. The car B2 uniformly gains speed to V and at the point Ctk.2 and connects with car B11 (state S4(t), mode Ctk.2) at the moment t4. After that moment, they follow together. During the motion the rear doors of car B2 open and the passengers who have to disembark at the next stop Oct.3 move from B2 to B11 car, and those passengers who must move further go over in-car B2 (in the reverse order from the last car to the first one).

The process of passenger transfer is monitored by the video camera of transfer unit 5. The passenger transfer should be performed during the period from the moment of the car's docking up t4 to the moment of unlocking t5. That is for the time ttran = t5−t4.

The block of fixation of passenger's transfer 5 after a period of time $0,75 \cdot t_{tran}$ from the beginning of transfer checks the presence of passengers in the crossing area. And if the passengers are detected in crossing area, computer 2 decides to reduce the speed of the train. Through the system bus of computer 2 the control unit of motion drive, 6 receives a command, which is executed by motion drive 7. The speed of the train will be reduced, which increases the transition time.

The forward car B1 which standing at the Oct.3 stop through the radio module 3 of the block fixing 5 is messaged about the delay of the train arrival to the point of the undocking Pctk.3. From this stopping point vehicle that staying forward will start a motion with delay. The train B11B2 will arrive late at the undocking point Pctk.3. After undocking, the front car B2 will run with speed V to the docking point Ctk.3 and catch up with car B1, which corresponds to the state of the transport system S6(t). Disconnected B11 car remains on Oct.3 for disembarkation and boarding of passengers. In other words, the delay that occurs while driving is leveled at Pctk. 3.

It should be noted, there is another delay variant. Let's consider it. It's a delay that appears at the time of disembarking and boarding passengers. Suppose, for example, that the video camera of block fixies the incoming and outgoing passengers 4, of the car B2, which is at the stop Oct.2 (state S2(t)), after a time $0,75 \cdot tboard$ (tboard–time of boarding) defines that not all passengers entered to the car. In this case, the computer decides to increase the boarding time. Through radio module 3 the rolling stock B11B21 that has undocking mode Pctk.2 is reported about increase the boarding time of forwarding car B2. Then the train B11B21 must reduce the speed and come to the stopping point on Oct.2 with a delay equal to the boarding time.

The states of the transport system S7(t) u S8(t) are similar to those described above. It should be noted that in establishing the working of the transport system that consists of n stations n wagons will be on a state of passenger boarding mode (Oct. i) and 2n wagons will be in motion. Wherein the first car of the train stops at odd stopping points, and the second car stops at even stopping points.

The passenger can get from any stop of the transport system to any other without delay. But for this aim, he will have to make transitions from the second car to the first along the train. If he does not want to do this, then he can remain in the carriage and go to his stop with the number of stops two times less than on ordinary public transport.

In Fig. 2, each odd Si (t)-state of the transport system corresponds to an even Si + 1 (t)–tate. Together they form pairs (S1 (t)−S2 (t), S3 (t)−S4 (t), etc.). The transition from the i - state to (i + 1) is carried out through the reformation zone. The transition from i to the (i + 1) state in Fig. 2 is shown by arrows. The reformation zone is the time interval from the moment of undocking Pctk.i through Oct.i. and up to the moment of Ctk.i docking.

A relatively long stationarity zone is located between the reformation zones (from Ctk.i to Pctк. (i + 1)). In this zone, there are no events, and the rolling stock moves uniformly, for example, from Ctk.2 to Ptk.3. The only single event that can disturb the operation of the system may be the speed reduction is discussed above.

Let's introduce the following time characteristics τ_f, τ_c, τ_z:

τ_f—reformation zone duration;
τ_c—stationary zone duration;
τ_z—duration of loading passengers in wagons.

The relationships between these durations are as follows:

$$\begin{cases} \tau fj << \tau cj, \forall j \in \overline{1, n} \\ \tau zj = \tau c(j-1) \end{cases}$$

In another word, the duration of the deformation zone is much shorter than the stationary zone. The loading time τzj of passengers at the j-th stop is equal to the duration τc (j-1) of the stationary zone of the (j−1)–driving. So, for the third stop, τzj = τc (j −) = t5 − t4. The duration τzj is a variable $j = \overline{1, n}$ that depends on the length of the run between stops, while τfj is constant.

Also, the distance from the undocking mode point Pctk.i to the stopping mode point Oct. i is equal to the distance from the stop Oct. i to the docking point Ctk.i for any stop, in another words L (Pctk.j, Oct.j) = L (Oct.j, Ctk. (j + 1)). Hence, equal times τt for car braking from the moment of undocking to stopping and accelerating of speed τp and from stopping point to the point of docking, that is, they are τt = τp = 0.5 τf. It should be noted, in addition, important technical characteristics of the system are the travel time τv between two stops and total time τn of one span, which is the sum of the loading time τzj of passengers at the stopping point j and the time of motion along the j span:

$$\tau_v = \tau_t + \tau_p + \tau_c = \tau_f + \tau_c \tag{5}$$

$$\tau_{nj} = \tau_{zj} + \tau_{cj} = \tau_{(j-1)}) + \tau_{cj}. \tag{6}$$

4 Conclusion

A new type of urban public transport is proposed in this chapter. This type of transport is capable to function in a saturation street and road traffic without interference from other vehicles also delivering a large number of passengers that is comparable to the metro power. The transport system is closed. That means the system functions independently from human participation. The information processes (information gathering, information processing, making a decision) follow continuously in such a system and form its basis. The single-vehicle unit in this system is an unmanned electric car. The economy can receive the following benefits from the project:

– creation of new competitive products not previously produced in the world;
– development of a new type of energy-efficient transport;
– saving hundreds of millions of dollars in fuel economy;
– this transport system in addition to high energy efficiency provides passengers with non-stop travel from the point of departure to the destination.

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Algorithm to Redistribute Capacity Between Transportation Network Sections

Alexander Galkin, Anton Sysoev, and Elena Khabibullina

Abstract A modification of the algorithm to control traffic flows in intelligent transportation systems is proposed. The basic algorithm uses the speed (or time) of movement as the transportation system functioning criterion, as well as the number of congested sections of the transport network. The algorithm is implemented as a solution to an optimization problem on the transportation network graph. The maximum carrying capacities of nodes and edges corresponding to transportation nodes and roads are set corresponding to the current condition. We also set the constraints on control options as possibilities to change the capacity. The second parameter used in the algorithm is the intensity of traffic flow on every element of the transportation network graph. The idea of the algorithm is to increase the carrying capacity of some edges with higher incoming traffic intensity at the expense of adjacent edges with extra carrying capacity compared to incoming flows. The algorithm repeats the procedures with redistributing flows as long as it is possible. It helps to reduce the total number of sections on the transportation network graph, where the intensities of incoming flows are higher than their capacities. The modification makes it possible to carry out the optimization of transportation system functioning integral criterion, which takes into account speed (or time) of transportation flows, traffic safety, and ecological damage. The control is based on increasing the capacity of overloaded sections at the expense of underloaded ones.

Keywords Intelligent transportation systems · Effectiveness criteria · Optimization · Control · Graphs

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1 Introduction

Developing effective schemes of regional transportation and logistics systems in Russia and great interest caused by the lack of similar projects could be explained by several reasons. First of all, it is an ability to connect such systems to the transportation monitoring system. Another reason is applying developed systems connected with artificial intelligence to the sphere of unmanned vehicles. Following this idea brings to the road maps of the Russian National Technological Initiative which is the program to support perspective developing Russian economics sectors. Road maps of the Initiative are based on studying the sphere of economic modernization and innovative development and include analysis results of each implementation step. According to the road maps, the Russian Government confirmed participation in 7 world economy markets, among which is the AutoNet market [1].

The modern development of information technology leads to its active implementation in almost all spheres of economic activity, which, in turn, leads to the transformation of existing processes. An example of such spheres is regional transportation systems. Regional social and economic state is largely determined by transportation systems. Therefore they are always given particular attention even at the level of the state. Many countries work out their development strategies. The current state and prospects of transportation systems development in Russia are analyzed as well [2]. In addition to the standard areas of development, including the modernization of infrastructure [3], almost all strategies emphasize the digitalization and intellectualization of transportation system control [4–7]. The advantage of these approaches implementation could be formulated as the less cost for project implementation, the less time for project implementation. The task of intellectualization is to automate traffic flows control. The solution to this problem could help to build effectively organize traffic flows via the transportation system depending on its current situation.

The approach to the control action can be built separately for each section of the transportation network, for example, an intersection, or comprehensively for a set of interconnected sections. The second way is more preferable because the optimal functioning of separate sections does not always lead to the optimal functioning of the system as a whole due to the lack of interrelations consideration. An example of complex control realization is the UTOPIA system [8]. The algorithm used in this system is based on the representation of a transportation network in the form of intersecting objects consisting of one regulated intersection located in the center and other intersections adjacent to it. Local techniques to optimize traffic flows within sections in transportation corridors such as ALINEA approaches [9] and modifications [10] could be taking account as examples.

2 Optimizing Transportation Network Functioning

2.1 Problem Statement

Graphs are the main tools to describe any transportation network [11–16]. The edges of the graph usually correspond to roads, while the vertices correspond to transport nodes, such as intersections. By setting certain characteristics for the graph elements, for example, traffic flow rate and capacity of roads, and incoming flow rates and capacities of transportation nodes, we can formalize the performance criteria of the transportation system [17, 18].

Let the graph of the transportation network for each i-th node has two parameters, namely $x_1^{(i)}$ is the incoming flow rate and $x_2^{(i)}$ it the maximum capacity; with each edge are also correlated two parameters, namely $e_1^{(i,j)}$ is the incoming flow rate and $e_2^{(i,j)}$ is the maximum capacity. By control actions through, for example, using different modes of traffic lights and connecting reversible roads $x_2^{(i)}$ and $e_2^{(i,j)}$ can be changed. To unify the control procedures, the capacity from the vertices should be transferred to the capacity on the edges. This can be done by splitting each vertex into two vertices. The first one includes all edges. One output with the bandwidth of the shared vertex will be directed to the second one. All the edges will go out of the second one.

Thus, for edges of the graph, there are matrices of capacities and traffic flows,

$$E_2 = \begin{bmatrix} e_2^{(1,1)} & e_2^{(1,2)} & \dots & e_2^{(1,n)} \\ e_2^{(2,1)} & e_2^{(2,2)} & \dots & e_2^{(2,n)} \\ \dots & \dots & \dots & \dots \\ e_2^{(n,1)} & e_2^{(n,2)} & \dots & e_2^{(n,n)} \end{bmatrix}, \tag{1}$$

$$E_1 = \begin{bmatrix} e_1^{(1,1)} & e_1^{(1,2)} & \dots & e_1^{(1,n)} \\ e_1^{(2,1)} & e_1^{(2,2)} & \dots & e_1^{(2,n)} \\ \dots & \dots & \dots & \dots \\ e_1^{(n,1)} & e_1^{(n,2)} & \dots & e_1^{(n,n)} \end{bmatrix}. \tag{2}$$

The efficiency criteria of the transportation system functioning can be divided into three main groups: criteria of speed (or time) of movement, safety criteria, and criteria of ecological compatibility [17].

As a criterion of the speed of movement there could be used the value of the flow rate to capacity ratio at an element of the transportation network:

$$k_1(e^{(k)}) = \frac{\lambda(x^{(i)})}{\mu(e^{(k)})}, \tag{3}$$

where $\lambda\left(x^{(i)}\right)$ is the flow fate entering the i-th vertex which is the beginning of the k-th edge and $\mu\left(e^{(k)}\right)$ is the capacity of the k-the edge.

The following criterion is used to assess the effectiveness of the transportation system as a whole:

$$K_1 = \min \sum_{k=1}^{m} c(e^{(k)}), \tag{4}$$

where $c(e^{(k)}) = \begin{cases} 1, \ k_1(e^{(k)}) > 1; \\ 0, \ k_1(e^{(k)}) \leq 1. \end{cases}$

As a safety criterion is used the probability of an accident on a particular element of the transportation network at the current level of traffic on the site

$$k_2(e^{(k)}) = g(\lambda(e^{(k)})). \tag{5}$$

To assess the effectiveness of the transportation system as a whole, the sum of probabilities of accidents on individual elements of the transportation system

$$K_2 = \min\left(\sum_{k=1}^{m} k_2(e^{(k)}) - \sum_{i,j=1}^{m} k_2(e^{(i)})k_2(e^{(j)}) + \ldots + (-1)^{m-1}k_2(e^{(1)})\ldots k_2(e^{(m)})\right). \tag{6}$$

As environmental criteria of the intelligent transportation system functioning it could be chosen exceeding indicators of the pollutants content emitted by transport on some elements of the transportation network

$$k_3(e^{(k)}) = \begin{cases} 0, \ V^k \leq V^0; \\ V^k - V^0, \ V^i > V^0, \end{cases} \tag{7}$$

where V^k is the pollutant content at the k-the section of the transportation system, V^0 is the maximum allowable content of the pollutant.

The integral criterion of the effectiveness is

$$K_3 = \min \sum_{i=1}^{n} k_3(e^{(k)}). \tag{8}$$

To combine three different types of criteria into a single one it is necessary to calculate their weighted average value. Moreover, taking into account different dimensionality and order of values, it is necessary to normalize these criteria beforehand and reduce them to dimensionless ones in a certain range, for example, [0;1]. In this case, the final criterion is

$$K = \alpha_1 K_1 + \alpha_2 K_2 + \alpha_3 K_3, \tag{9}$$

where $\Sigma_{i-1}^{3}\alpha_i = 1,\ \alpha_i \geq 0$ Particular values of the coefficients should be determined by expert evaluation and can change depending on the current priorities. Normally, this is done by specialists in organizing transportation systems.

As the result, the problem is set as follows. It is necessary to minimize the integral efficiency criterion (9) for the given transportation network in the form of the graph and current matrices of flow rates (1) and capacities (2) due to the change of carrying capacities matrix

$$\min_{E_2} K. \tag{10}$$

The criterion optimization is carried out by allowable capacity changes, which can lead to changes in traffic rates.

The algorithm to solve this problem can be used in real-time traffic control systems. The information, collected from sources of fixation, for example, installed video cameras, is processed (cf. study [19]) and is brought in a system as current traffic flow rates of transportation network sections. Using these current values, the algorithm determines the optimal capacity redistribution, taking into account the limitations, for example, the possibility of reconfiguration of the traffic light mode. The frequency of using this algorithm for capacity redistribution should be decided for every particular section.

2.2 The Algorithm to Solve the Problem

In studies [20, 21] it is given the algorithm and the example of its implementation for capacity redistribution with criterion (4). The idea of the algorithm for solving this problem is to find overloaded sections of the transportation system, to increase the capacity of overloaded sections by using the free capacity of underloaded sections, and to redistribute the capacity. The general scheme of the algorithm is shown in Fig. 1.

To estimate the edge load, we determine the vector $U = [U_1,\ldots,U_n]^{\mathrm{T}}$ where $U_i = \sum_{j\in X} e_1^{(j,i)} - \sum_{j\in X} e_2^{(i,j)}$. The overloaded sections are determined from the condition $U_i > 0$ For each overloaded section the possibility to increase its capacity at the expense of underloaded adjacent sections is determined. To achieve this it is necessary to find all edges $e^{(i,j)}$ such that $U_j < 0$. Then the total possibility to increase the capacity of the i-th node is $\sum_{j\in X_j} |U_j|$, where X_j is the set of vertices $x^{(j)}$, adjacent to vertex $x^{(i)}$. The algorithm to find congested sections, for which there is a possibility to increase the carrying capacity, is shown in Fig. 2.

The next step is the direct redistribution of edges capacity with the formula

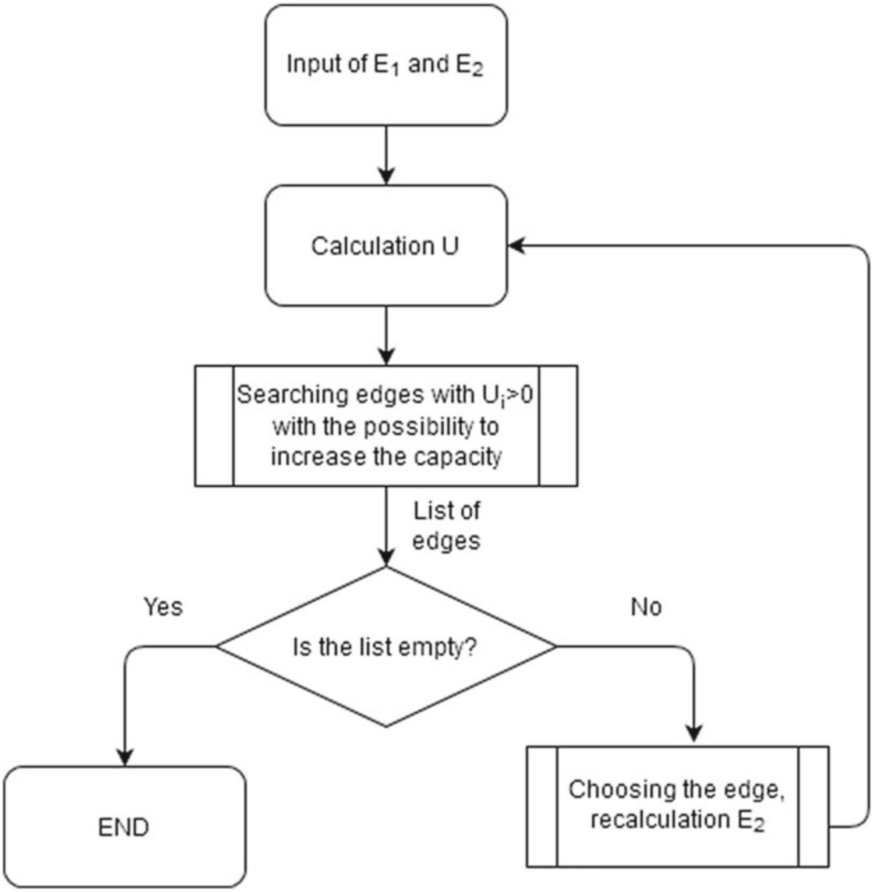

Fig. 1 Scheme of the algorithm to redistribute traffic flows

$$e_{2new}^{(i,j)} = e_2^{(i,j)} + \frac{\left|U_j\right|}{\sum\limits_{j \in X_j} \left|U_j\right|} \min[|U_i|, \sum_{j \in X_j} \left|U_j\right|]. \qquad (11)$$

The algorithm repeats the procedures with redistribution of flows as long as it is possible. This reduces the total number of sections on the transportation network graph, where the incoming flow rates are higher than their capacities.

3 The Modification of the Algorithm

The algorithm presented in paragraph 2.2 has a number of limitations, the main of which is to take into account only the criterion on the speed of movement. Criteria

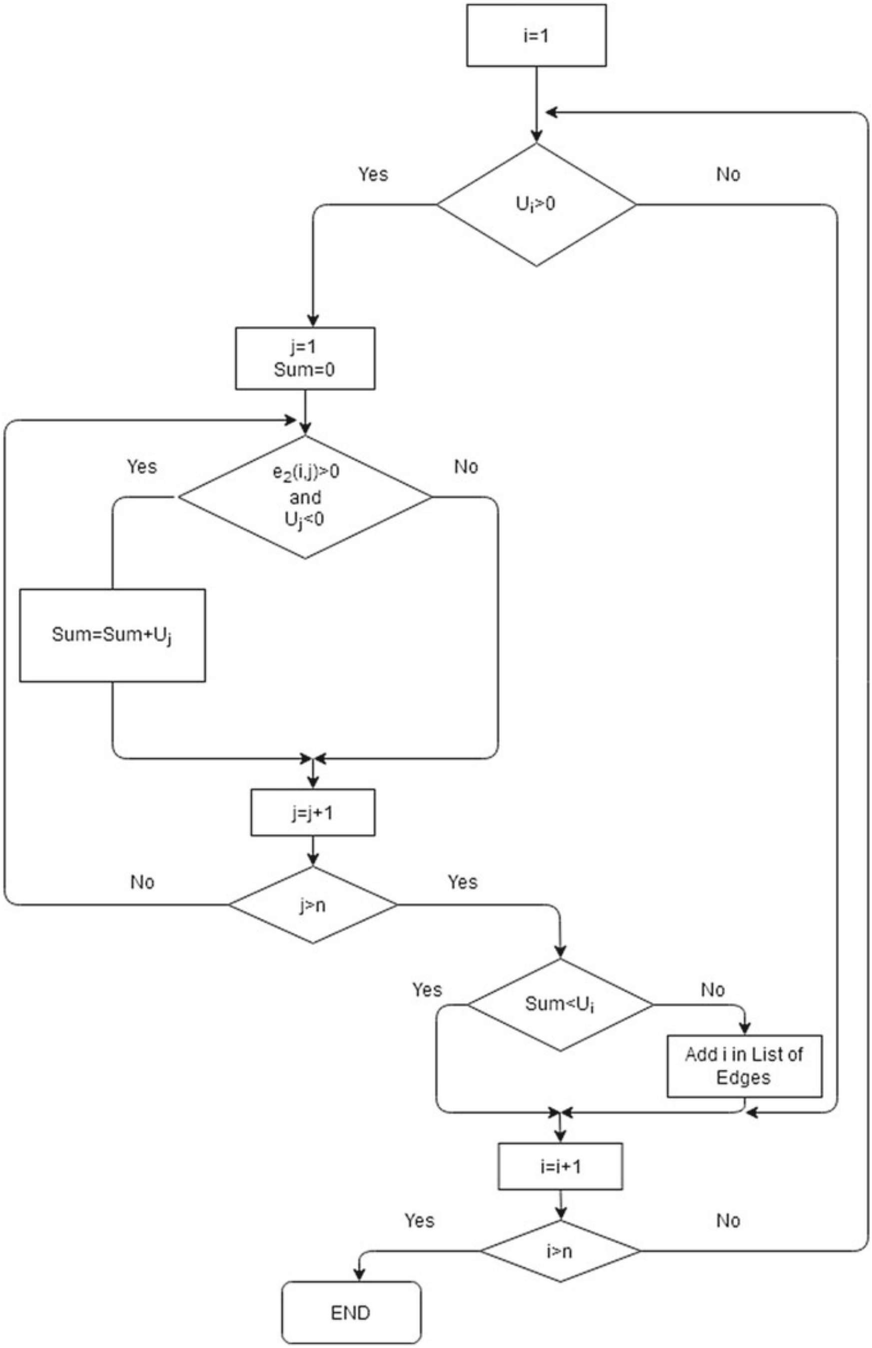

Fig. 2 The algorithm to find sections to redistribute traffic flows

(6) and (8) for each section of the transportation network are functional dependences on traffic flows. However this dependence is not linear, in this connection a simple replacement of redistribution criterion on the integral one, taking into account speed of moving, safety, and ecological compatibility, will not work. That is why its modification is proposed. Let us make the following assumptions: (1) traffic flow changes only at those sections where the capacity increases; (2) criteria (5) and (7) increase with the increase of flow rate. Then, at the stage of determining the possibility of increasing the capacity of congested sections, it is necessary to check the additional condition

$$\alpha_1 \geq \alpha_2\left(k_2\left(e_{1new}^{(i,j)}\right) - k_2\left(e_1^{(i,j)}\right)\right) + \alpha_3\left(k_3\left(e_{1new}^{(i,j)}\right) - k_3\left(e_1^{(i,j)}\right)\right). \quad (12)$$

The implementation of this condition ensures that the gain in the final criterion (9) from the reduction of congested sections will not be offset by an increase in accidents and pollution. It is possible to increase the capacity of this section according to (9) only if this condition is fulfilled.

The alternative of the presented approach to the optimization of the multi-criteria problem can be the approach to achieve the Pareto efficiency according to the criteria (4), (6), and (8). But considering the assumptions stated above, optimization of criteria (6) and (8) is possible only due to a decrease of traffic rate at some sections, which, in its turn, can be achieved only by a decrease of carrying capacity of these sections. But then the value of criterion (4) will increase because there will be added sections with incoming traffic rate exceeding their capacity. It means that it is impossible to improve the values of criteria (6) and (8) without worsening criterion (4).

4 Numerical Example

Figure 3 shows the graph corresponding to the transportation network. For each edge, its capacity and current traffic flow are specified, respectively. To the left of

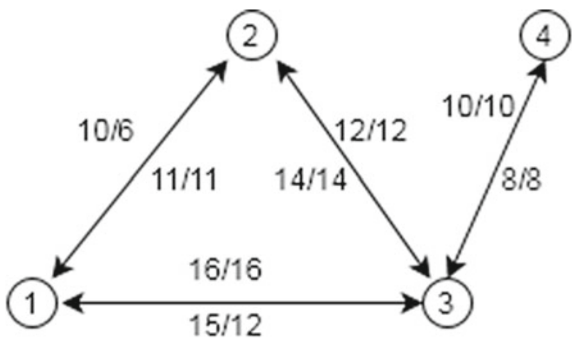

Fig. 3 The graph of transportation network

the edge are the labels in the bottom-up direction, to the right top-down, to the top are left–right, and to the bottom are right-left.

It is also specified the capacity of the nodes corresponding to the intersections $x^{(2)} = [23;\ 21;\ 39;\ 20]$. The capacity of nodes is determined by the ability to pass the intersection in all possible directions of traffic. The capacity in a particular direction is part of the intersection capacity and is determined by the current traffic light setting. To set these capacities, each vertex has to be divided into as many vertices as there are exits. Besides, each vertex is split into two vertices to transfer carrying capacities from vertices to edges and unify calculations. As the result we have 16 vertices [1.2; 1.3; 1.2*; 1.3*; 2.1; 2.3; 2.1*; 2.3*; 3.1; 3.2; 3.4; 3.1*; 3.2*; 3.4*; 4.3; 4.3*]. The initial matrices of capacities and traffic flows are shown in Figs. 4 and 5. Let us redistribute the carrying capacities by optimizing criterion (4).

At the first step we calculate the vector $U = [3.15385; -3.15385; -4.; -4.; 3.95652; -4.95652; -9.375; 0.; -4.76224; -2.69231; 0.454545; -3.; 0.; 0.; -10.; 0.]$. We get the criterion value $\Sigma_{k=1}^{16} c\left(e^{(k)}\right) = 3$. The vector contains three positive elements corresponding to vertices 1.2, 2.1, and 3.4. Each of these vertices has an adjacent vertex that has a capacity reserve. We increase the capacity of vertex 1.2 at

$$\begin{pmatrix}
0. & 0. & 8.84615 & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 14.1538 & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 10. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 9.33333 & 6.66667 & 0. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 10.0435 & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 10.9565 & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
0. & 11. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 4.375 & 5. & 0. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 7.2 & 0. & 4.8 & 0. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 15. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 14. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 10. & 0. & 0. & 10. & 0. & 0. \\
15. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 14. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 10. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 20. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 4.13793 & 3.86207 & 0. & 0. & 0. & 0. & 0. & 0.
\end{pmatrix}$$

Fig. 4 The matrix of capacities

$$\begin{pmatrix}
0. & 0. & 6. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 12. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 6. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 7. & 5. & 0. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 11. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 12. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
0. & 11. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 6.54545 & 0. & 5.45455 & 0. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 12. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 14. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 10. & 0. & 0. \\
12. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 14. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 10. & 0. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 8. \\
0. & 0. & 0. & 0. & 0. & 0. & 0. & 0. & 3.69231 & 4.30769 & 0. & 0. & 0. & 0. & 0. & 0.
\end{pmatrix}$$

Fig. 5 The matrix of flow rates

0.	0.	12.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	11.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	10.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	9.33333	6.66667	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	10.0435	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	10.9565	0.	0.	0.	0.	0.	0.	0.	0.
0.	11.	0.	0.	0.	0.	0.	0.	0.	4.375	5.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	7.2	0.	4.8	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	14.5455	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	14.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	10.4545	0.	0.
15.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	14.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	10.4545	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	20.
0.	0.	0.	0.	0.	0.	0.	0.	4.13793	3.86207	0.	0.	0.	0.	0.	0.

Fig. 6 Optimized capacities matrix

the expense of the capacity of vertex 1.3. In this case, the traffic flow along the edge (1.2; 1.2*) will also change.

At the first step we calculate the new value of the vector $U = [0.; 0.; -0.84615; -4.; 3.95652; -1.80267; -9.375; 0.; -4.76224; -2.69231; 0.454545; -3.; 0.; 0.; -10.; 0.]$. We get the criterion value $\Sigma_{k=1}^{16} c\left(e^{(k)}\right) = 2$. The vector contains two positive elements corresponding to vertices 2.1 and 3.4. Each of these vertices has a contiguous vertex with capacity reserve, but vertex 2.1 has the total capacity reserve of contiguous vertices less than necessary. So we increase the capacity of vertex 3.4 at the expense of the capacity of 3.1. At that, the intensity of traffic along the edge (3.4; 3.4*) will also change.

The new calculated value of the vector $U = [0.; 0.; -0.84615; -4.; 3.95652; -1.80267; -9.375; 0.; -4.30769; -2.69231; 0.; -3.; 0.; 0.; -9.54546; 0.]$. We get the criterion value $\Sigma_{k=1}^{16} c\left(e^{(k)}\right) = 1$. Вектор содержит один положительный элемент, соответствующий вершинам 2.1. We obtain the criterion value Vector contains one positive element corresponding to vertices 2.1. The total stock of carrying capacities of adjacent vertices is less than required, so the computation is complete. The final matrix of carrying capacity has the following form (Fig. 6).

Let's consider now the redistribution of capacities using the criterion (9) and values of coefficients $\alpha_1 = 0.5$, $\alpha_2 = 0$, $\alpha_3 = 0.5$. We use the content of a single pollutant with a maximum permissible value of 100 and the dependence on the intensity of $V^k(e^{(k)}) = \left(e_1^{(k)}\right)^2$. Then the condition (12) must be checked before redistributing the traffic flows. For the first step $k_3\left(e_2^{(1.2,1.2*)}\right) = 0$, since $V^k(e^{(1.2,1.2*)}) = \left(e_1^{(1.2,1.2*)}\right)^2 = 36 \leq 100$, and $k_3\left(e_{2new}^{(1.2,1.2*)}\right) = 0$, since $V^k(e^{(1.2,1.2*)}) = \left(e_1^{(1.2,1.2*)}\right)^2 = 83.79 \leq 100$. Hence, the condition $0.5 \geq 0.5\left(k_3\left(e_{2new}^{(i,j)}\right) - k_3\left(e_2^{(i,j)}\right)\right)$ is satisfied and the redistribution is carried out. At the second step $k_3\left(e_2^{(3.4,3.4*)}\right) = 0$, since $V^k(e^{(3.4,3.4*)}) = \left(e_1^{(3.4,3.4*)}\right)^2 = 100 \leq 100$, and $k_3\left(e_{2new}^{(3.4,3.4*)}\right) = 9.3$, since $V^k(e^{(3.4,3.4*)}) = \left(e_1^{(3.4,3.4*)}\right)^2 = 109.3 > 100$. The

0.	0.	12.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	11.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	10.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	9.33333	6.66667	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	10.0435	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	10.9565	0.	0.	0.	0.	0.	0.	0.	0.
0.	11.	0.	0.	0.	0.	0.	0.	0.	4.375	5.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	7.2	0.	4.8	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	15.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	14.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	10.	0.	0.
15.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	14.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	10.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	20.
0.	0.	0.	0.	0.	0.	0.	0.	4.13793	3.86207	0.	0.	0.	0.	0.	0.

Fig. 7 Optimized capacities matrix taking into account integral criterion

condition (12) is not satisfied and the redistribution of capacities cannot be performed. Then the final matrix of carrying capacities will have the following form (Fig. 7).

5 Conclusion

The chapter presents an approach to comparing the functioning of intelligent transportation systems. For comparison, criteria are singled out and methods of their calculation are defined. The developed algorithm of carrying capacity redistribution of transportation network sections in case of taking into account the movement speed criterion is presented. A check of the additional condition is offered, which makes it possible to carry out the capacity redistribution taking into account the final criterion, which includes besides motion speed also safety and ecological compatibility.

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Analysis of the Reachability of Stops in the Route Network of Urban Passenger Transport

Tatyana P. Ogar, Elena G. Krushel, Ilya V. Stepanchenko, Aleksandr E. Panfilov, and I. M. Kharitonov

Abstract Data on the distribution of population density by urban areas are collected and analyzed. To improve the accuracy of the study, each of the districts is further divided into tiles. The location of passenger public transport stops in residential areas and areas of socially significant objects is investigated. Isochron of accessibility of the main objects of attraction of passengers is constructed. Using the algorithm of the minimum cost of the way for each route of the transport network, the distance that the passenger can travel in 15 and 30 min is found. On the route network, a graph is drawn up, the vines of which are public transport stops. The weights of the graph correspond to the time of movement of vehicles from one stop to another. As a result of the Floyd-Warshall algorithm, the shortest paths between all the vertices of the graph are found. The obtained data can be used in the transport network model to solve a multi-criteria optimization problem. When you add a new version, you can calculate a new route with minimal time costs. Based on the results of the study, a number of recommendations were developed for urban passenger public transport enterprises; data for the implementation of the transport network model were prepared.

Keywords Transport system · Accessibility of stops · Population density · The Floyd-Warshall algorithm

1 Introduction

One of the most important indicators of the transport service system of the city population [1], which affect the level of satisfaction of citizens, along with the cost of travel, the comfort of vehicles, is the time spent on the road. This indicator is composite and includes the following components:

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- time spent from home to public transport stop;
- travel time;
- time from the arrival stop to the destination.

A number of scientific papers [2–4] solve the problems of optimizing the transport network. Data on existing public transport stops are used as input data for building transport models. In the proposed solutions for the reorganization of the route map of the city [5], when calculating the travel time, the time that a passenger spends on the road from the point of departure to the public transport stop and from the arrival stop to the final destination of the route is not taken into account. There are cases when a large amount of time interval on foot has a more negative impact on the satisfaction of citizens with the standard of living than the increased travel time on public transport [6].

To regulate the provision of urban infrastructure facilities with passenger public transport stops in Russia, a social standard for public transport services has been developed [7]. This document sets the maximum distances of the shortest pedestrian path [8] from the boundaries of the sections of various types of objects to the stopping points.

2 Population Density Analysis

To build a realistic model of passenger generation at public transport stops [9], it is necessary to determine the number of people living within each of the stops of the urban transport network.

The following is a study of the urban passenger transport network on the example of the city of Volgograd, whose population is equal to 1 million people.

At the first stage of the study, an analysis of the city's population density was performed [10]. The official data on the population of the city, including the number of each of the city's districts, was taken as the initial data.

The entire geographical area occupied by the city was divided into tiles in the UTM [11] coordinate system. The size of each tile is assumed to be 500 × 500 m. The total number of tiles occupied by urban infrastructure objects and related to the city's transport system was 1,020.

For the distribution of a population geographically within each district were used open data services street view, namely Google, Yandex, and map data: Google, Yandex, 2GIS, OpenStreetMap. According to the received data, the houses in each of the tiles were counted. At the same time, multi-storey buildings were reduced in terms of the number of residents to single-storey ones using the coefficients of a number of storeys, the number of apartments per floor. A multi-storey house is a number (usually dozens) of single-storey houses at one point, that is, a mechanism was used to bring all the houses to individual houses. Separately, the settlement settlements were processed, the number of which is known. The houses of these settlements were excluded from the number of houses of the corresponding tile. In accordance with this constant and the number of listed houses, the number of inhabitants of each tile was determined.

The density of the distribution of the listed houses in each district of the city was assumed to be a constant (that is, it is assumed that each listed house has the same number of inhabitants for a given district) [12].

The errors in measuring the number of residents (relative to official data) for each of the districts are in the range of 0.1–1.7%. The overall average error in determining the number is 0.6%. The main sources of the resulting error: finding a multi-storey building on the border of tiles; error in the calculation of houses.

Information about each tile is collected according to the following characteristics –

coordinates of the borders of each tile (xmin, ymax; ymin, xmax);

number of bus stops;

the area to which the tile belongs;

the number of inhabitants of this tile.

An example of the population distribution is shown in Table 1.

A general view of the population density of the entire city is shown in Fig. 1.

For further analysis, all nearby stops (in the area of one intersection) were combined under one name. The resulting number of residents was distributed among the bus stops, depending on the proximity of the houses to the bus stop. An example of the distribution is shown in Table 1.

Table 2 Example of the distribution of residents by public transport stops.

Name of the stop Area Number of residents in the area of the stop.

The error in the distribution of the number of residents in the districts of the city relative to the total population is 0.02%.

Due to the peculiarities of the city, the authors introduced several additions:

1. Two bus stops were introduced artificially. They are necessary for modeling the passenger flow of ring routes, their number is conditional-1/2 people, which will lead to zero number of passengers at the final stopping points of the ring routes.

Table 1 Example of the distribution of residents by tiles

№	xmin	xmax	ymin	ymax	Number of bus stops	District	Number of residents
447	4,958,200	4,959,700	6,243,466	6,244,966	2	District 3	1345
448	4,959,700	4,961,200	6,243,466	6,244,966	2	District 3	1066
449	4,961,200	4,962,700	6,243,466	6,244,966	2	District 3	789
450	4,962,700	4,964,200	6,243,466	6,244,966	0	District 4	0
451	4,964,200	4,965,700	6,243,466	6,244,966	4	District 4	2583
452	4,965,700	4,967,200	6,243,466	6,244,966	0	District 4	13,949
453	4,967,200	4,968,700	6,243,466	6,244,966	10	District	14,912
454	4,968,700	4,970,200	6,243,466	6,244,966	2	District 4	5429
455	4,970,200	4,971,700	6,243,466	6,244,966	0	District 5	0

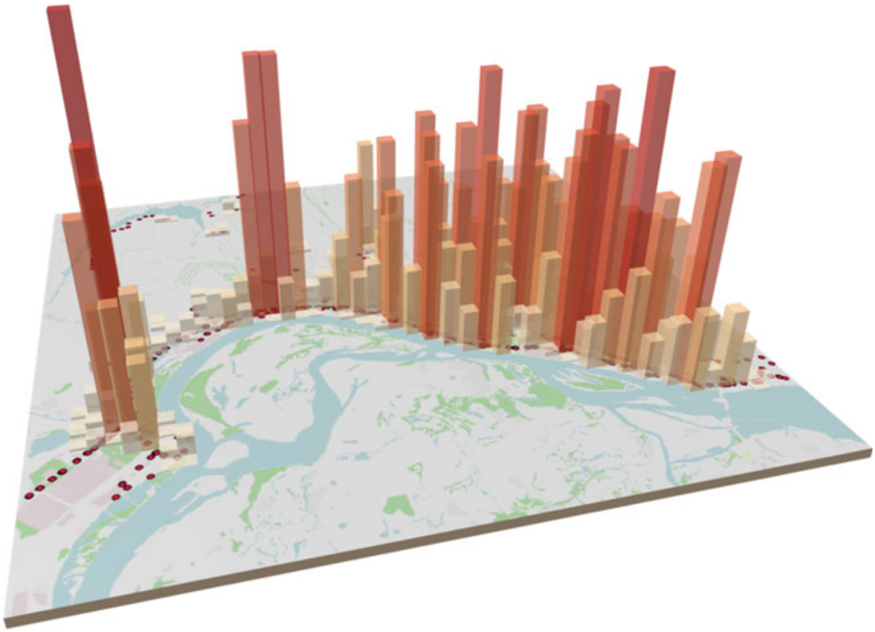

Fig. 1 Distribution of the population density of Volgograd

Table 2 Example of the distribution of residents by public transport stops

Name of the stop	District	Number of residents in the area of the stop
Ost_1	District 1	6472
Ost _2	District 2	2174
Ost _3	District 2	312

2. Added a number of bus stops with a population of fewer than 100 people. This is necessary, first of all, for stops located within suburban areas. Based on the fact that officially no one lives in dacha plots, but in fact, this is not the case, it was decided to appoint a certain number of "conditional residents".
3. Some bus stops have the same number of inhabitants, exactly up to a person. In fact, this is not the case, but if the stops were located in the same tile (and neighboring tiles do not affect the number of residents—there are other stops), then the number of residents of the tile was divided proportionally between the stops. Thus, the specified number is the median value.

3 Analysis of the Location of Stops on Route Lines of Passenger Public Land Transport and Their Accessibility to the Population

To further analysis of the results of the survey using mathematical and statistical methods, the respondents ’ responses were normalized [8]. Each response was assigned a corresponding coefficient in the range from 0 to 1.

The social standard of public transport services regulates the distance of the shortest pedestrian route from the point of the border of the land plot on which the object is located to the nearest stop point, depending on the category of the object:

- apartment building;
- individual residential building;
- trade enterprises with a trading floor area of 1000 m^2 or more;
- polyclinics and hospitals of the municipal, regional, and federal health care system, institutions (departments) of social services for citizens;
- external transport terminals.

The Volgograd region is one of the subjects of the Russian Federation with special natural and climatic conditions, for which the recommended distance to the first three objects from the above list is reduced by 100 m. compared to other subjects.

The authors analyzed the implementation of the norms of subclause 3.1.1 of this social standard by routes served by the municipal transport enterprise of the city. For a convenient visual representation, the data obtained is reflected on the city map.

The city in question has some infrastructural features [13]. In the route diagram, the reference and auxiliary routes are allocated in the ratio of 1:3, respectively. A generalized diagram of the auxiliary route network is shown in Fig. 2.

As an example of the implementation of the norms of the maximum distances of the shortest pedestrian route from the point of the border of the land plot on which the object is located to the nearest stop point, which is served by a regular route, consider the location of stops in the residential areas of one of the settlement settlements (P3). The established standard value for an individual residential building is no more than 800 m (for the city of The norm that is allowed for the subjects of the Russian Federation with special natural and climatic conditions, 700 m) can also be applied; for an apartment building, the value is set to no more than 500 m (400 m for the city of Volgograd).

Figure 3 shows the areas covered by the bus stops on the routes served by the company. Circles with a radius of 800 m are shown in blue (the second inner circle is 700 m)—in the zones of individual residential buildings. Circles with a radius of 500 m are shown in purple (the second inner circle is 400 m)—in areas of multi-storey buildings. The centers of the circles are the stopping points of the M12 and M24 routes.

Fig. 2 Generalized scheme of the auxiliary route network

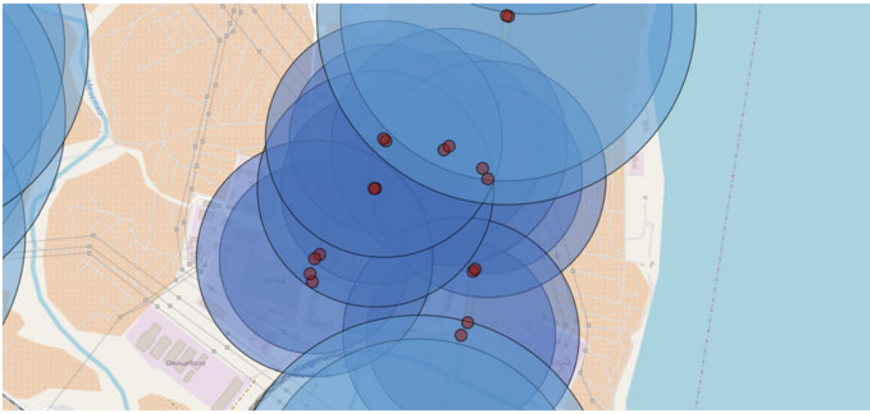

Fig. 3 Coverage of residential areas in the village area P3. Routes M12, M24

The routes of the enterprise cover a fairly large number of residential buildings, this is primarily due to the peculiarities of the location of residential buildings and roads. According to the results of the study, the coverage of rural settlements in terms of the number of residents of rural settlements is 63.7%.

In drawing 4 an example of checking the compliance with the norms of the maximum distances of the shortest pedestrian path from the borders of the sections of objects to the stopping points for polyclinics, hospitals (all health systems), social service institutions for citizens, terminals of external transport (the standard value is 300 m) is given. In the considered section, the reference route network covers 5 objects of this category. The centers of the circles are social objects. The radius of each circle is 300 m. The points on the map correspond to the stops of the M5 and M8 routes (Fig. 4).

For trade enterprises with a sales floor area of 1000 m^2 or more, a value of no more than 500 m is set (for the city of Volgograd, the norm of 400 m can also be applied).

The entire route network of the enterprise covers a maximum of 19 trade enterprises out of 30. The percentage of coverage is 63.3.

In drawing 5 an example of a plot with two large retail halls located in the center of the orange circles is given. The points on the map are located according to the public transport stops on the M10, M7, and M19 routes (Fig. 5).

Based on the data on the reachability of various types of infrastructure objects, so-called "isochron" were constructed [14]. Isochron is lined on the map that passes

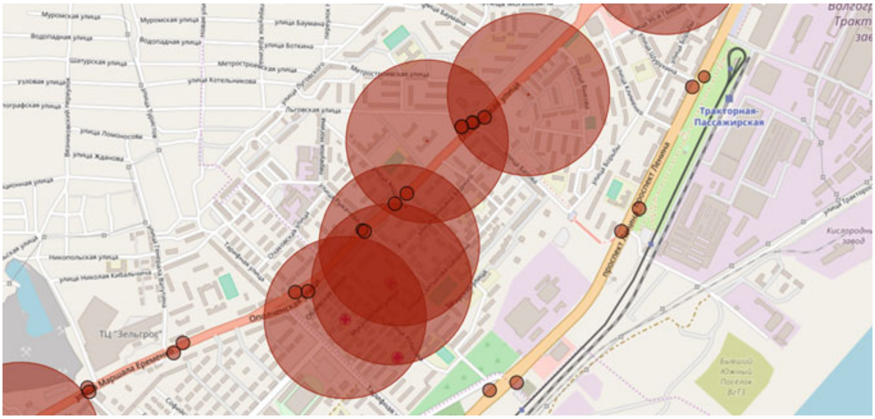

Fig. 4 Coverage of social facilities (routes M5, M8)

Fig. 5 Coverage of trade enterprises (routes M10, M7, and M19)

Fig. 6 Accessibility of the object of attraction of passengers

through points equidistant in time of reachability from the selected location. In this case, the isochron shows the accessibility of the main objects of attraction of passengers in two-time intervals: 30 and 15 min. When constructing an isochron, the location of public transport stops on existing routes is taken into account.

On the isochrones, the red circles show the objects of attraction of passenger traffic, and the blue circles show the achievable stops on the route network. The dark blue area corresponds to the 15-min isochron, and the light blue area corresponds to the 30-min isochron (Fig. 6).

The software product created according to the requirements should allow the user to assess the reachability of territories from the selected stop. At the same time, it is necessary to take into account the time limits of the path: the first reachability zone is 15 min, the second reachability zone is 30 min.

The analysis shows that, in general, the accessibility of the objects of attraction for passengers is satisfactory for large cities [15]. The route network allows passengers to move between the main attractions in a reasonable time. In each 30-min isochron, there are medical institutions and commercial enterprises [17–20].

4 Calculating Routes with the Minimum Cost of Paths

The data obtained during the analysis of the reachability of stops is the basis for building a transport model [16]. Thus, the criterion for optimizing the public transport network includes such an item as reducing the time for a trip on the passenger side.

To create a route map with a minimum cost of the path, the authors proposed to calculate it using the Floyd-Warshall algorithm [21]. The passenger transport network is described from the point of view of graph theory. This algorithm allows you to determine the shortest paths between all the vertices of the graph. To perform the Floyd-Warshall algorithm, you need to build two matrices [22]:

– the matrix of weights $W^k = [w_{ij}]$ of the graph G_m;
– the path matrix $Z^k = [z_{ij}]$, where is the ordinal number of the matrix.

The initial weight matrix W^0 is filled in as follows:

1. element $w_{ij} = a(i, j)$, where $a(i, j)$ is the weight of the path from vertex i to vertex j
2. w_{ij} is assigned the value ∞ if the graph does not have an edge (i, j) oriented from the ith vertex to the jth.
3. $w_{ij} = 0$ in all cases where $i = j$.

Based on the original matrix W (0), the algorithm generates a sequence of matrices W(0), W(2),…, W(k),…, W(min). The constituent elements of the finite matrix W (min) are the elements $w_{ij}(min)$, which correspond to the shortest distances between the i-th and j-th vertices in the graph Gm.

The weight matrix W(k) is calculated based on the matrix W(k − 1). the formula for calculating each element of the new matrix is as follows:

$$w_{ij}^{(k)} = \min(w_{ij}^{(k-1)}, w_{ir}^{(k-1)} + w_{ri}^{(k-1)}) \quad (1)$$

A single matrix of weights, W (k) is not sufficient to solve the problem. In addition to it, a path matrix P(k) is formed. This matrix is used to form, in addition to the shortest distances, sequences of transitions from one vertex to another, i.e. paths. The original path matrix P (0) contains elements that are formed according to the principle given below:

– the element p_{ij} (0)is assigned the value i if the corresponding element w_{ij} (0) in the weight matrix W (0) of the graph Gm is not equal to∞, and is not one of the elements of the main diagonal of the matrix;
– in all other cases, the $p_{ij}(0)$ element of the path matrix P (0) is assigned the value 0.

The calculation of the sequence of path matrices P(1), P(2),…, P(k),…, P(m) occurs simultaneously with the calculation of the weight matrices. According to the Floyd-Warshel algorithm, in the resulting path matrix P(m), the element of the matrix $p_{ij}(m)$ corresponds to the vertex that precedes the vertex j in the shortest path from the ith to the jth vertex.

The shortest path from the ith vertex to the jth vertex is formed from a sequence of vertices i,…, u − 2, u − 1, u, j, where $u = p_{ij}(m)$, $u - 1 = p_{iu}(m)$, u − 2 = pu, u − 1(m), etc.until it reaches the initial vertex i.

Next, we will consider the operation of the Floyd-Warshall algorithm for a section of the route network using the example of a section of a public transport route.

The algorithm allows calculating the travel time from all stops to every possible one. At the same time, when the program is running, calculations will be made once, and you will not need to take up computer resources each time you select a specific stop to calculate the cost of the path (unlike, for example, Dijkstra or Ford-Bellman algorithms).

In the calculations, the step of the calculated grid is 20 m, the speed of buses on the route is 20 km / h, and the speed of pedestrians off the roads is 2 km / h. The characteristics of the road network [23] were considered unchanged (traffic capacity, congestion level, no mutual influence of users of the transport network).

At the first stage, a graph was created for each of the existing routes of the Volgograd city's transport network (Gm, where m is the route number). Each graph has Nm vertices. Each graph is oriented [24] because there are circular routes where vehicles move in only one direction. The graph shows the following elements:

- vertexes corresponding to existing transport network stops (indicated by the stop number in the general list of stops—Ost1, Ost2, Ost3,…, OstN);
- the graph edges are constructed according to public transport routes;
- weights—the time spent on the road from one stop on the route to another (indicated in minutes).

The algorithm can be used not only to form a route network of the minimum cost of the path between existing stops, but can also be used when adding a new stop to the line.

An example of a section of the route network represented as a set of graphs with a driving stop (Ost 6) is shown in Fig. 7. Lines of different types correspond to three different routes. The blue color indicates the possible paths from the entered stop.

First, the initial weight and path matrices for this section of the route network are compiled, together with the new proposed stop (Tables 3 and 4):

$$W^{\wedge}0Z^{\wedge}0$$

На следующем этапе с помощью алгоритма Флойда-Уоршелла находится расстояние и путь от каждой вершины до каждой (таблицы 5.6) (Tables 5 and 6).

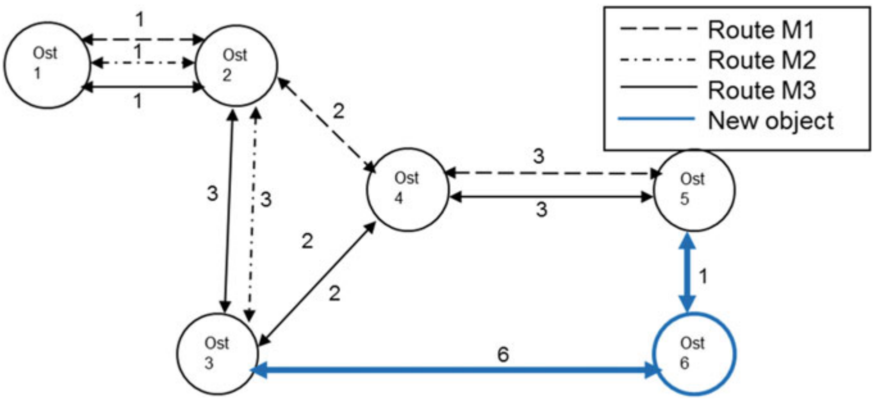

Fig. 7 A section of the transport network represented as graphs

Table 3 Initial weight matrix W^0

	Ost1	Ost2	Ost3	Ost4	Ost5	Ost6
Ost1	0	1	∞	∞	∞	∞
Ost2	1	0	3	2	∞	∞
Ost3	∞	3	0	2	∞	6
Ost4	∞	2	2	0	3	∞
Ost5	∞	∞	∞	3	0	1
Ost6	∞	∞	6	∞	1	0

Table 4 Initial weight matrix Z^0

	Ost1	Ost2	Ost3	Ost4	Ost5	Ost6
Ost1	1	1	0	0	0	0
Ost2	2	2	2	2	0	0
Ost3	0	3	3	3	0	3
Ost4	0	4	4	4	4	0
Ost5	0	0	0	5	5	5
Ost6	0	0	6	0	6	6

Table 5 Initial weight matrix W^n

	Ost1	Ost2	Ost3	Ost4	Ost5	Ost6
Ost1	0	1	4	3	6	7
Ost2	1	0	3	2	5	6
Ost3	4	3	0	2	5	6
Ost4	3	2	2	0	3	4
Ost5	6	5	5	3	0	1
Ost6	7	6	6	4	1	0

Table 6 Initial weight matrix Z^n

	Ost1	Ost2	Ost3	Ost4	Ost5	Ost6
Ost1	1	1	2	2	2,4	2,4,5
Ost2	2	2	2	2	4	4,5
Ost3	2	3	3	3	4	3
Ost4	2	4	4	4	4	5
Ost5	4,2	4	4	5	5	5
Ost6	5,4,2	5,4	6	5	6	6

4. The final stage involves constructing an isochron of the reachability of city objects from each point selected by the user.

5 Conclusion

The analysis of the reachability of public transport stops showed that there are zones in the city that do not meet the social standard of public transport services, i.e. the distance between infrastructure objects of a certain type and the nearest stopping points exceeds the established one. In addition, there are sections of the route network where there is an excess of stops.

The isochron construction shows that, in general, the availability of objects of attraction for passengers is satisfactory for large cities when carrying out regular flights on the routes of the enterprise. In each 30-min isochron, there are medical institutions and trade enterprises.

From the survey of the population carried out in related works, the most significant problems in the field of public transport services by bus routes, according to citizens, are the intervals of bus movement and the cost of travel.

Based on the analysis performed and taking into account the questionnaire, the Company is recommended to:

Ensure that on the reference routes served by the Enterprise, the interval of movement of vehicles is not more than 10 min.

Consider the option of parity coverage of social facilities and rural settlements between all major carriers in the city, thereby reducing the number of inefficient routes and at the same time not reducing the performance of indicators of the social standard.

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Process Management of Transportation and Logistics Projects Based on Simulation

Alexey Rozhko and Anna A. Khanova

Abstract The key factors of the development of the transport and logistics industry in the context of the digital transformation of society are highlighted. The definition of a transport and logistics project is given, and its main processes are highlighted (production/delivery of the cargoes to the warehouse/terminal, handling operations with the cargoes, storage of the cargoes, transportation of the cargoes), and additional processes (conversion/reconstruction of the cargoes, flow of funds). The specific features of the transport and logistics process, including many stochastic factors that determine the need for the use of simulation modeling methods, are noted. From the point of view of the theory of organizational systems, the structure of the transport and logistics project management system is proposed. The managed subjects—processes of the transport and logistics project are described in detail and structured. A model of decision-making by managed subjects is constructed. An example of a simulation model of a transport and logistics project for the delivery of equipment for a wind power plant is considered. The description of the submodels of the simulation model is given in accordance with the developed generalized management structure of the transport and logistics process. Experiments were carried out, optimal production intensities were identified for a transport and logistics project for the delivery of equipment for a wind power plant.

Keywords Transport and logistics project · Management · Simulation modeling · Experiments

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1 Introduction

According to research by PricewaterhouseCoopers (PWC) company, the transportation and logistics industry is significantly impacted by five key factors: digitalization, changes in the international trading, changes in the main processes due to the new software implementation, changes in dynamics of the domestic markets, changes in the main processes due to the emerging technology implementation [1]. Data from a survey of the heads of transport and logistics companies have shown that 54% of them expect to increase revenues from digitalization (Fig. 1). Innovative business modeling tools and simulation modeling software should be first of all on the basis of the digital transformation of transport and logistics companies [2]. The simulation model is fundamentally a "digitally alter ego" of a real transport and logistics system, aimed at improving manageability, obtaining additional information, allowing to get a fairly accurate forecast of the future system condition, improving the digital solutions and interaction with partners through all the value chain [3, 4].

Analysis of the works by foreign and Russian authors [5, 6] indicates a lack of effective management tooling for large transport and logistics projects and their life

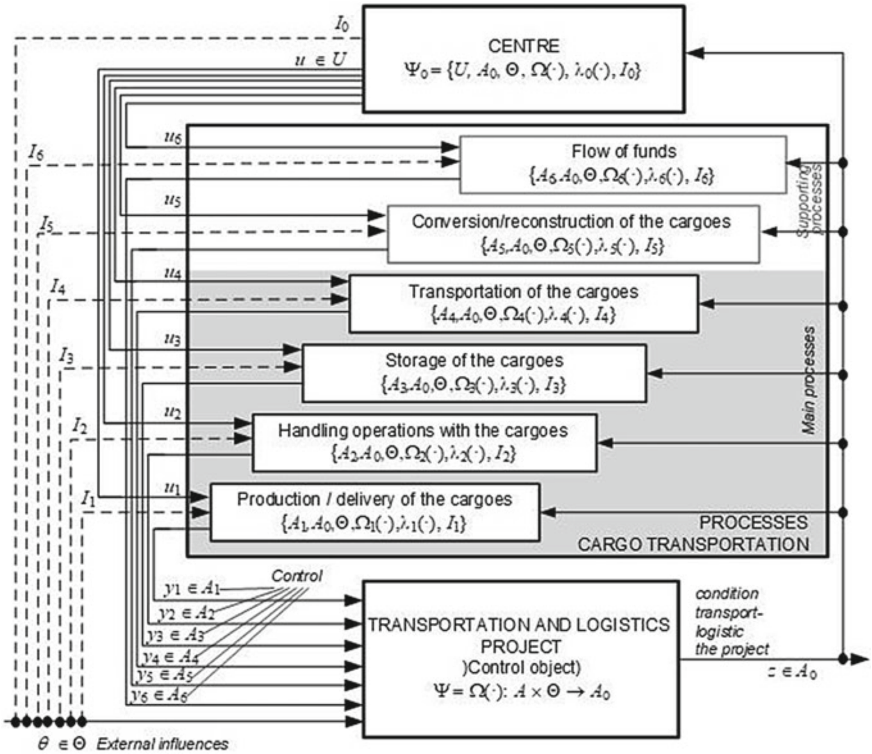

Fig. 1 The management system structure of the transport and logistics project

cycle processes under the conditions of the external social and economic environment instability, a large-scale factor, and a high cost of error and risk. The task of increasing the management effectiveness of transport and logistics projects on the basis of simulation modeling becomes currently important.

2 Peculiarities of the Implementation Processes of Transport and Logistics Projects

The project in the transport and logistics systems refers to the processes associated with the planning and optimizing of the cargo transportation, engineering of the supply chains, designing and optimizing of the warehouse operations, etc. Preparing and planning a transport and logistics project requires a collection of the information about the project start time, dates of the manufacture/intensity of the cargo manufacture; analysis of the various transportation routes, technical characteristics of terminals, vehicles, and the cargoes; surveys of the routes/terminals with the involvement of experts (development of the special projects, a survey of bridges/berths, etc.). When organizing the cargoes transportation, the following main processes and operations are distinguished:

– production/delivery of the cargoes to the warehouse/terminal (MDC—Manufacturing Delivery Cargoes);
– handling operations with the cargoes (CH—Cargo Handling);
– storage of the cargoes (CS—Cargo Storage);
– transportation of the cargoes (CT—Cargo Transportation);
– conversion/reconstruction of the cargoes (CRC—Conversion / Reconstruction Cargo);
– the flow of funds (FF—Flow of Funds).

The typical task of the transport and logistics project is organizing the process of the cargo (equipment) transportation from the production site to the installation site. The cargoes can be both standard and non-standard, for example, heavy oversized cargo (i.e. the dimensions and weight of the cargo exceed the dimensions allowed during transportation). Organization of the heavy oversized cargo transportation requires the performance of the preparatory operations: a survey of the routes; selection of the terminals, the storage sites, lifting equipment; developing the special projects of the placing cargo on the vehicles and the special project of the cargo handling operations, etc. Non-standard cargo transportations in logistics are called projects [7].

Usually, the customer provides the following data: dimensions and weight of the cargoes, place of the production/shipment, place of the delivery, transportation deadline, production intensity of the cargoes can be set. Further, the transport company specialist has to determine the optimal transportation routes, determine the transport and handling equipment for cargo transportation, terminals and calculate the project budget. Despite the existence of the transport and logistics project budget standard calculation schemes [8], as the rule, many unknown variables remain.

The components of the cargoes (equipment) are produced in different cities and countries, with different production intensities. It is necessary for the installation assembling, that all the components of the cargoes (equipment) arrive at the construction site at the same time. But practice shows that deviations emerge very often in the transport and logistics project associated with changes in the production intensity, availability of the transport and handling equipment, transportation of the cargoes (equipment), etc. Such deviations can affect the behavior of the system as a whole, in most cases, it is expressed in the project budget increase. The budget is usually calculated analytically in spreadsheets, on the averaged data and known (linear) dependencies, does not take into account non-linear/non-obvious dependencies, cause-and-effect relationships.

Peculiarities of the transport and logistics projects implementation determine the notional complexity and uncertainty of the study object (as the node of the various elements interaction: water/road/rail/air transport, cargoes (equipment), handling equipment and service personnel, stochastically reacting to the control actions [9]), the high dimension of the analysis problem, etc.). Formalization of the task of increasing the efficiency of the transport and logistics project management process is necessary, taking into account impossibility of the using the monotonous mathematical tool and impediment of the mathematical description with the formal models since many processes have a stochastic nature. The use of the simulation modeling will allow to study in-depth and in detail all processes of the transport and logistics projects at the stage of the planning, as well as to investigate changes in the system behavior due to changes in input data, playing various scenarios on each stage of the project. Modern software of the simulation modeling support GIS, which allows indicating the place of the production/shipment and the place of unloading/delivery of the cargoes on the map, as well as the route of the cargo transportation. The simulation model needs to be developed taking into account the cargoes transportation and the flows of funds.

3 System Analysis of the Transport and Logistics Project Management Structure

In the terminology of the management science of the organizational systems, the control system structure for the transport and logistics project is presented as the combination of the following elements (Fig. 1) [10]:

- controlling authority (center);
- managed subjects—the transport and logistics project processes (MDC, CH, CS, CT, CRC, FF);
- a managed object (of the transport and logistics project) at the entry of which there are control actions $y = (y_1, y_2, y_3, y_4, y_5, y_6) \in A = (A_1, A_2, A_3, A_4, A_5,$

A_6), at the output, there is an object performance result (condition of the transport and logistic project) $z \in A_0$, which depends on the action $y \in A$ and situation $\theta \in \Theta$ in the following way: $z = \omega(y, \theta)$. Feedback provides cargo transportation processes and the center with information on the transport and logistics project status.

Interests and preferences of the participants of the "Transport and logistics project" system—center and managed subjects—are expressed by their target functions (utility functions). As the preferences of the center λ0(·) are determined, are determined, including, on the range A0 of possible results of activity of the managed subjects, and the latter ones depend on the actions of the managed subjects and the environments, then management consists in encouraging the managed subjects by the center to choose certain actions [11]. The decision-making model by managed subjects MDC, CH, CS, CT, CRC, FF is described by the following finite sequence [12]:

$$\Psi_i = \{A_i, A_0, \Theta, \Omega_i(\cdot), \lambda(\cdot), I_i\}, \text{ где } i \in N = \{1, \ldots, 6\},$$

i.e. by the range: of admissible actions $A = (A_1, A_2, A_3, A_4, A_5, A_6)$, of activity admissible results A_0, of the possible values of the situation (uncertainty) Θ; of the functions: utility functions $\lambda_1(\cdot), \lambda_2(\cdot), \ldots, \lambda_6(\cdot)$ for the managed subjects MDC, CH, CS, CT, CRC, FF and the relationship between actions, environments and activity result $\Omega_1(\cdot), \Omega_2(\cdot), \ldots, \Omega_6(\cdot)$ for MDC, CH, CS, CT, CRC, FF; as well as the information $I = (I_1, I_2, I_3, I_4, I_5, I_6)$, which is possessed by the managed subjects MDC, CH, CS, CT, CRC, FF at the moment of making decisions.

The laws $\Omega_1(\cdot), \Omega_2(\cdot), \ldots, \Omega_6(\cdot)$ are known to all participants of the system and cannot be changed. This assumption corresponds to the fixed technology of the managed objects functioning (berths, warehouses, handling and transport equipment, etc.). It can also be assumed that the range of the possible environments Θ in the functioning of the transport and logistics project is known to all participants of the system and is fixed (in order to fulfill this assumption, this range can always be chosen wide enough, limiting the possible values of the environments in each specific case with the information available to the managed subjects). Let us distinguish three groups of variables (elements of the finite sequences Ψ, that can change)—admissible range A and A_0, utility functions $\lambda_1(\cdot), \lambda_2(\cdot), \ldots, \lambda_6(\cdot)$ and information $I = (I_1, I_2, I_3, I_4, I_5, I_6)$ [12].

The decision-making model is described by the finite sequence

$$\Psi_0 = \{U, A_0, \Theta, \Omega(\cdot), \lambda_0(\cdot), I_0\},$$

where U is management; A_0 is a range of admissible results of the activities of the managed subjects; Θ is a range of the environments; $\Omega(\cdot)$ is the dependence of the activity result on the action and the environment; $\lambda_0(\cdot)$ is the utility function; I_0 is information, possessed by the center for making a decision. The "actions" of the center (the strategies chosen by it) are managements $u = (u_1, u_2, u_3, u_4, u_5, u_6)$.

The set of the strategies $y_{-i} = (y_1, \ldots, y_{i+1}, y_{i-1}, \ldots, y_6) \in A_{-i} = \prod_{j \neq i} A_j$ is called the environment for the i-th managed subject (MDC, CH, CS, CT, CRC, FF). The task of managing a transport and logistics project as an organizational system can be formally formulated as follows: to find admissible management that has an acceptable efficiency, i.e. $E(u) \rightarrow \max_{u \in U}$. Value $E(u)$, $u \in U$ is called the management efficiency and is determined by the chosen strategy [13].

The presented structure of the transport and logistics project management system (Fig. 1) allows to consider each process separately and subsequently from these units to build a simulation model with the necessary parameters, to make adjustments for each unit depending on the conditions of the task [14–16]. In the real transport and logistics project, each process (MDC, CH, CS, CT, CRC, FF) is decomposed into several sub-processes, depending on the types of cargoes involved in this project.

4 The Simulation Model of the Transport and Logistics Project

Let us consider the presented approaches for managing a specific transport and logistics project for the delivery of equipment for the wind power plant (WPP). It is necessary to deliver the blades manufactured at the plant in Bangalore (India), parts of the wind turbine mast from Kemerovo (Russia), equipment (parts of the nacelle, generator, hub, container) from the port of Rotterdam (Netherlands) to the construction site in Zarevo (Russia). It is necessary to deliver a part of the equipment to Volgodonsk, Russia for the conversion.

The weight and dimensions of the equipment, the dates of the equipment readiness, the intensity of equipment production, the site of delivery of the equipment are known. The simulation model is implemented in the software AnyLogic and is represented by the following sub-models in accordance with the decomposition of the cargo transportation process (Fig. 1). When developing the simulation model, we used 2 methods (approach): discrete event and agent-based. The agents were ports, terminals, vehicles, vessels, etc. All processes in the simulation model were specified explicitly.

1. Production/delivery of the cargoes to the warehouse/terminal. In the simulation modeling, this process is used to generate requests—the cargoes (manufacturing of the blades at the plant) or the arrival of the requests—the cargoes to the warehouse/terminal (delivery of the cargoes (equipment) to the terminal/port) [17]. In Fig. 2, the block marked in red simulates this process.
2. Handling operations with the cargoes. In simulation modeling, this process is used before or after cargo transportation [18]. In this case, this is the loading of the cargoes from the warehouse (after the process of the cargoes storage) to

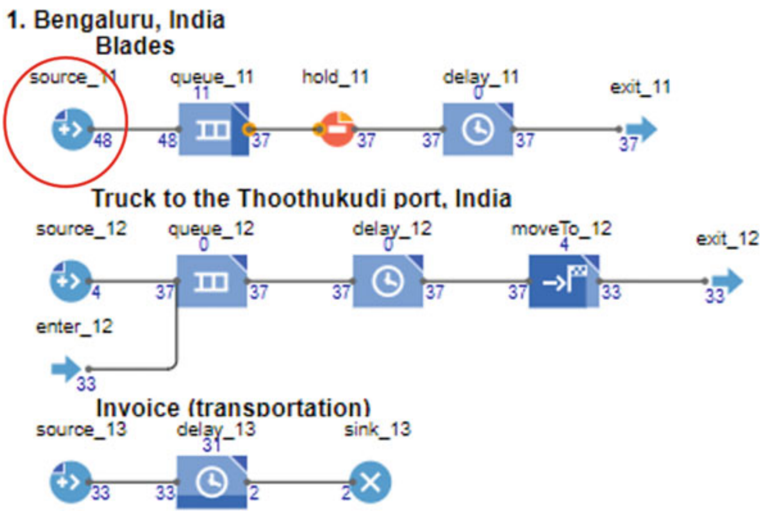

Fig. 2 Production/delivery of the cargoes to the warehouse/terminal (on the example of the blades delivery)

the vehicle (followed by the process of the cargo transportation). In Fig. 3, the block marked in red simulates this process.

3. Storage of the cargoes. In the simulation modeling, this process is used after the process unloading of the cargoes from the vehicle or before loading the cargoes to the vehicle [19]. In this case, the process is applied when the cargoes arrive at the warehouse in the port/terminal for temporary storage (accumulation of the shipload lot, customs clearance, etc.). In Fig. 4, the block marked in red simulates this process.

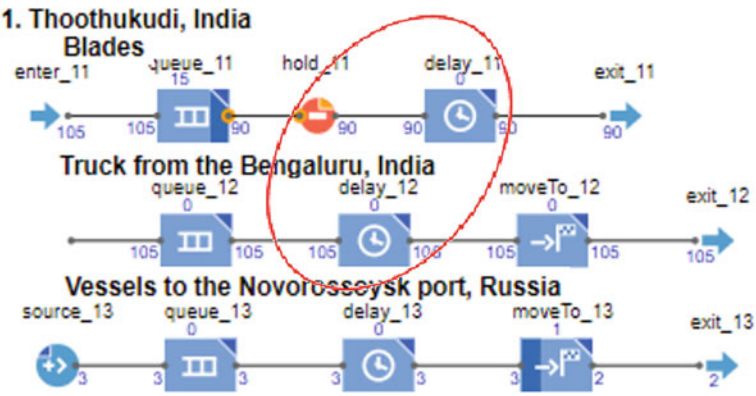

Fig. 3 Handling operations with the cargoes (blades loading to the vessel)

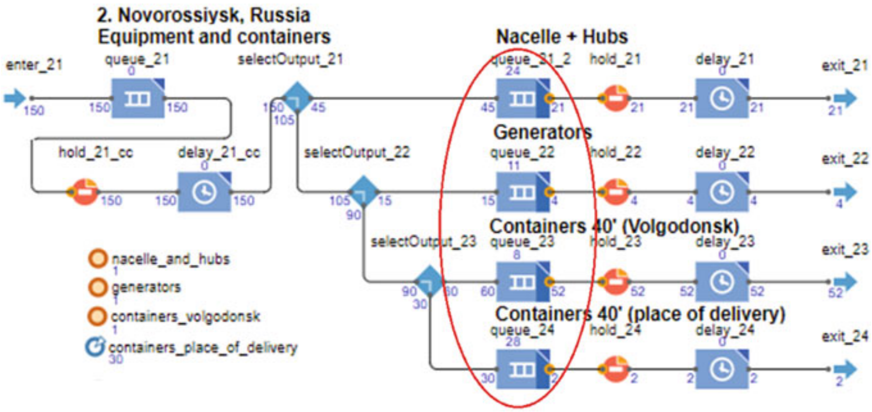

Fig. 4 Storage of the cargoes (blades storage in the port)

4. Transportation of the cargoes. In the simulation modeling, this process is used for the actual cargo transportation on the vehicle from the place of loading to the place of unloading. In Fig. 5, the block marked in red simulates this process.
5. Conversion/reconstruction of the cargoes (auxiliary process). In the simulation modeling, this process is used when modifying the cargoes (equipment) or installing additional equipment, adjustment, etc. In Fig. 6, the block marked in red simulates this process.
6. The flow of funds (auxiliary process). This process is used when paying for the services of the subcontractors and reimbursing the costs incurred from the freight forwarder in the form of both prepayment and post-payment for the

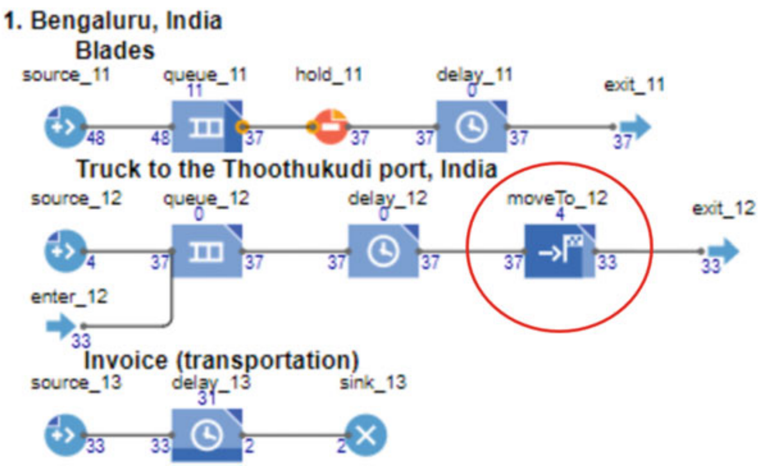

Fig. 5 Transportation of the cargoes (blades transportation on the vehicle)

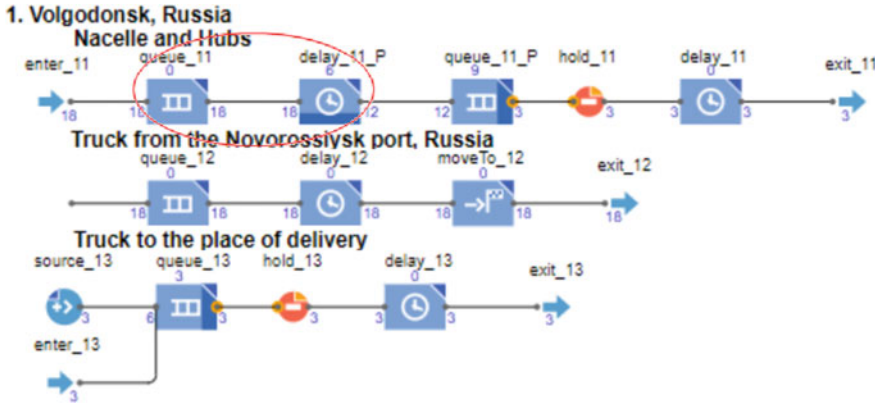

Fig. 6 Conversion/reconstruction of the cargoes (auxiliary process)

provided services and materials. In Fig. 7, the block marked in red simulates this process.

In the course of experiments with the simulation model of the transport and logistics project, the following runs were performed:

- Run 0—initial parameters (production intensity of the assembled mast part in the Kemerovo—2 units per month; production intensity of the blades in Bangalore—7 units per week);
- Run 1—the production intensity of the mast part has been increased to 3 units per month;
- Run 2, 3, 4—the production intensity of the blades has been reduced to 4, 3, 2 units per week, respectively (Fig. 8).

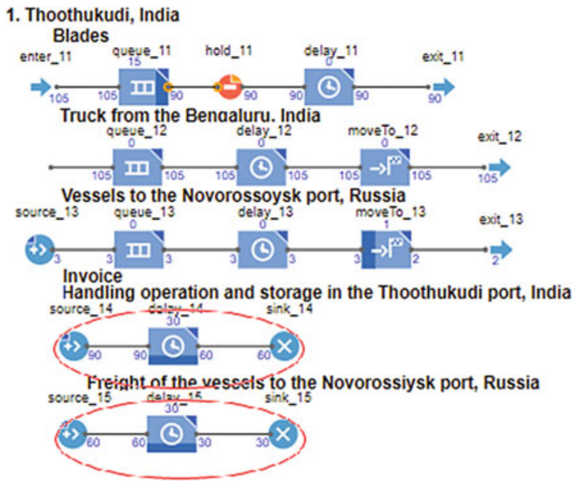

Fig. 7 The flow of funds (auxiliary process)

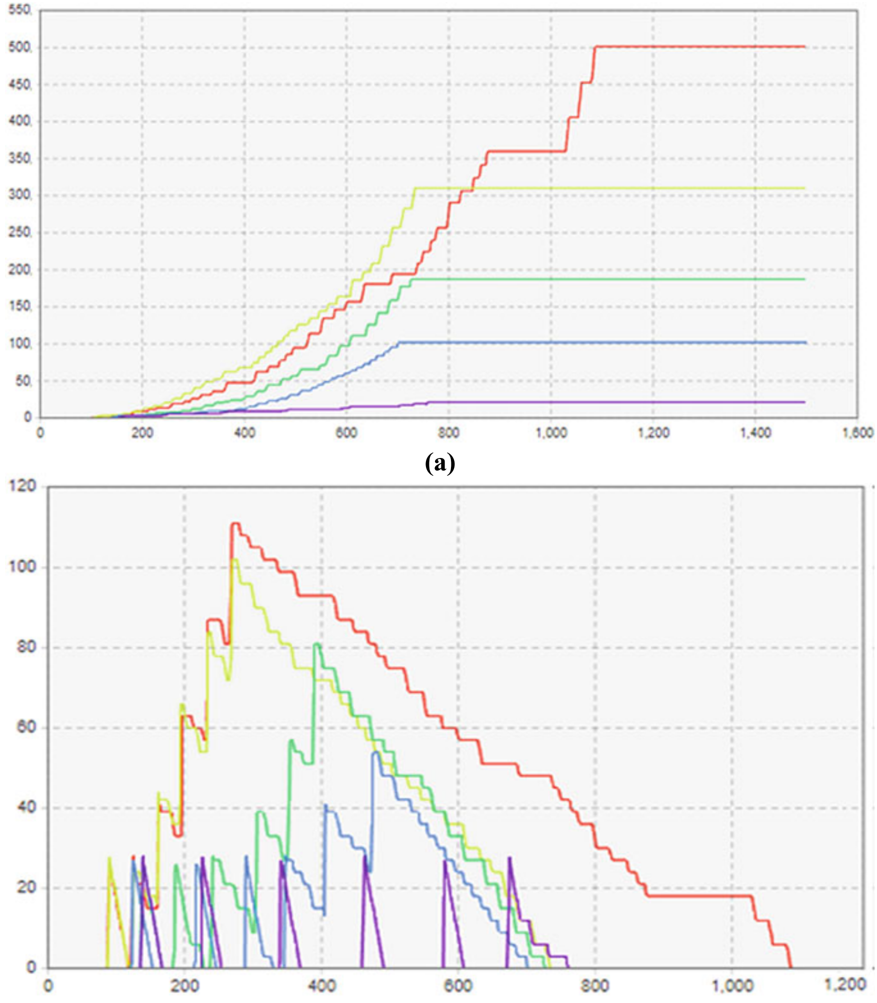

Fig. 8 Simulation modeling results (a—is the total cost of the blades storage at the terminal of the Novorossiysk port (ths. USD), b—is the number of the blades stored at the terminal of the Novorossiysk port (units))

As a result of the runs, the optimal production intensity of the blades and assembled masts (Run 3) was determined, at which the number of the blades stored at a time in the Novorossiysk port will not exceed 60 units. As the result, the projected budget for the storage costs in the port is reduced from ths. USD 500 to ths. USD 250. Develop of a simulation model for the transportation of the equipment will allow solving the following management tasks:

- To determine the optimal routes for the cargo (equipment) transportation at the planning stage of the transport and logistics project;
- To reveal and analyze bottlenecks at the stage of the transport and logistics project planning;
- The analysis performed of the various scenarios for the cargo (equipment) transportation of the transport and logistics project;
- Analyzed the need for the resources at the planning stage of the transport and logistics project (vehicles, handling equipment, etc.);
- Provided forecast for the full cost of the transport and logistic project;
- Provided forecast for the timing of the cargoes (equipment) transportation.

The use of simulation modeling will allow detailed development of transport and logistics projects at the planning stage, as well as to investigate changes in the system behavior in connection with changing input data, playing various scenarios at each stage of the project [20]. Modern simulation packages support GIS, which allows you to indicate on the map the place of production and the place of the cargoes unloading, as well as the route of movement.

5 Conclusion

The conceptual structure of the transport and logistics project management has been developed. The managed subjects of the transport and logistics project have been structured from the point of view of the organizational systems: production/delivery of the cargoes to the warehouse/terminal, handling operations with the cargoes, storage of the cargoes, transportation of the cargoes, conversion/reconstruction of the cargoes, the flow of funds. The peculiarities are highlighted and the management actions, parameters of the external environment, and the status of the transport and logistics process are considered in detail. The simulation model for the equipment delivery for the wind power plant is described in detail. The sub-models of the simulation model are described, fragments of its schemes are given. Based on the experiments, the planning practicability of the transport and logistics projects on the basis of the simulation modeling technology is shown.

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Algorithm for Generating Passenger Traffic at Stops for the Urban Transport System Model

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Abstract A model for generating passenger traffic at city public transport stops has been developed. The key parameters, features, and limitations of the passenger traffic model are outlined. The categories of passengers that have characteristic features of behavior during daily movement around the city are identified. Two tasks were solved: an algorithm for generating hourly passenger traffic (based on the Poisson distribution) was developed; an algorithm for selecting a destination station for each passenger was created, taking into account its attractiveness. The total number of passengers arriving at city public transport stops, distributed per hour, is calculated. The results of the summation are presented in the form of a graph. The developed model of passenger traffic is planned to be used in the organization of management of the transport complex of the city to study the passenger flow between the stops of the city, as well as to improve the operation of the passenger transport system.

Keywords Passenger transport · Passenger traffic model · Generation of passengers · Choice of stops · The attractiveness of a stop

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1 Introduction

Conducting computational experiments with models of the functioning of the transport system is one of the approaches to assessing the quality of management of urban transport services. To implement a model of the transport system of a given city, it is necessary to take into account the specifics of its passenger transport system, places of residence of the population and objects of attraction of passengers, and the peculiarities of passenger flows [1].

Modeling is one of the main research methods in most fields of knowledge, as well as a scientifically based method for evaluating the characteristics of complex systems, in particular transport systems [2]. Modeling is the most effective way to solve problems related to optimizing the structure of transport hubs and the movement of passenger traffic within them, taking into account the variety of transport situations and their random manifestations [3].

A complex model of a public transport system includes the following elements: a model for generating passengers at stops, a model for transporting passengers by public transport, and a model for managing public transport traffic.

In this chapter, we considered a model of passenger generation at public transport stops, which consists of two parts: 1) hourly passenger traffic from the departure stops to the destination districts; 2) minute-by-minute passenger traffic with the addition of the destination stop.

The passenger traffic generation model should take into account the following specificity [4]:

1. The infrastructure of any city includes various objects to attract passengers (educational institutions, shopping and entertainment centers, healthcare companies, etc.).
2. The objects of attraction are distributed in each district of the city. This distribution is often irregular, which affects the passenger traffic to them.
3. Passenger traffic to some large objects does not depend on the places of residence of citizens. Such points of attraction include hospitals, higher educational institutions.
4. The passenger's choice of the leaving stop among the nearest stops is considered random.
5. The passenger's choice of the destination stop is random. The location of the attraction objects and the type of passengers (student, working, retired) are taken into account.

2 Problem Statement

The development of an algorithm for generating passenger traffic at stops for the urban transport system model is the goal of the research.

This model generates passenger traffic in the time interval from 6:00 to 21:00. This is due to the working hours of passenger transport companies, as well as insignificant passenger traffic at night. There are 3 periods in this time interval: morning time (from 6:00 to 11:00), daytime time (from 11:00 to 16:00), and evening time (from 16:00 to 21:00).

Passengers are divided into 2 categories, which have their preferences in transport movements. The first category is students and workers, who in the morning mainly go from the district of residence to the district of accumulation of objects of attraction of the population (enterprises, secondary and higher educational institutions), at lunchtime they move inside the district, and in the evening they return to the district of residence. The second category is schoolchildren and pensioners. The difference between the passenger traffic of the second category and the first is that in the morning it moves mainly in the region of residence, where schools and places of frequent visits of pensioners are located.

The generator, which simulates the appearance of passengers at stops, is implemented based on the Poisson distribution, which determines the random number of people arriving in a fixed time (one hour), provided that the events are independent of each other. The output data of the generator is information on each individual passenger—its departure and destination stop, the time of appearance at the stop, the passenger category.

Passenger traffic in the morning and afternoon hours is calculated according to the data of long-term observation of specialists and the results of a survey of residents. Evening passenger traffic is determined so that the population of the district at the end of the working day (at 21:00) is almost the same as at the beginning of the working day (at 6:00) [5, 6].

Limitations: the developed algorithm has the following limitations:

1. students go to schools only in their district of residence;
2. children under the age of six move only with their parents, so they do not participate in the calculations.

3 Data Sources

To build a model for generating passenger traffic, data from various sources were used—static data from open sources; materials provided by urban passenger transport enterprises; results of a survey of residents on the issues of public transport services [7–9].

The initial data of the passenger traffic model includes:

(1) names and number of city districts, names, and number of stops included in each district [10];
(2) population in the city, in each district, in the neighborhood of the location of each stop;
(3) the attraction of a stop as a destination stop;

(4) distribution of passenger movements between districts depending on the time of day (morning, afternoon, evening) and the category of passengers (students and workers, schoolchildren and pensioners) [11];
(5) numbers of routes passing through the stops [10].

Additionally, the parameters defined by the experts are entered in the model:

(1) percentage of citizens using public transport;
(2) percentage of public transport passengers who prefer minibusses;
(3) the number of passenger trips, depending on their categories;
(4) probabilities of choosing a destination stop depending on the attractiveness of the stop;
(5) the probability of choosing a stop without a transfer, with a single transfer, or a random choice of a stop [12].

4 Research Tasks

Within the framework of the developed model of passenger traffic generation, the following tasks are considered:

(1) generating hourly passenger traffic from the departure stop to each district based on the Poisson distribution;
(2) selection of destination stops based on their attractiveness and generation of per-minute passenger traffic.

5 Generating an Hourly Passenger Traffic

Figure 1 shows a generalized algorithm for the operation of the passenger flow generation module.

After loading the source data, which in this work were placed in MS Excel, the number of citizens by the district is determined. The number of potential passengers, and therefore their trips, depends on the number of citizens by district. Passengers moving between city districts during the day change the number of potential trips from the districts in the following hours [13–16].

A number of trips of first-class passengers (students and workers) y_HourWork(i, h) for the h-th hour from the i-th district can be estimated in terms of the number of citizens of the i-th district remaining in this district per h-th hour x(i), and the probability of moving passengers districts and hours timeDist(i, h):

$$\text{y\_HourWork}(i,\ h) = x(i) * \text{PubT} * (1 - \text{RTaxi}) * \text{TripDay} * \text{timeDist}(i,\ h) \tag{1}$$

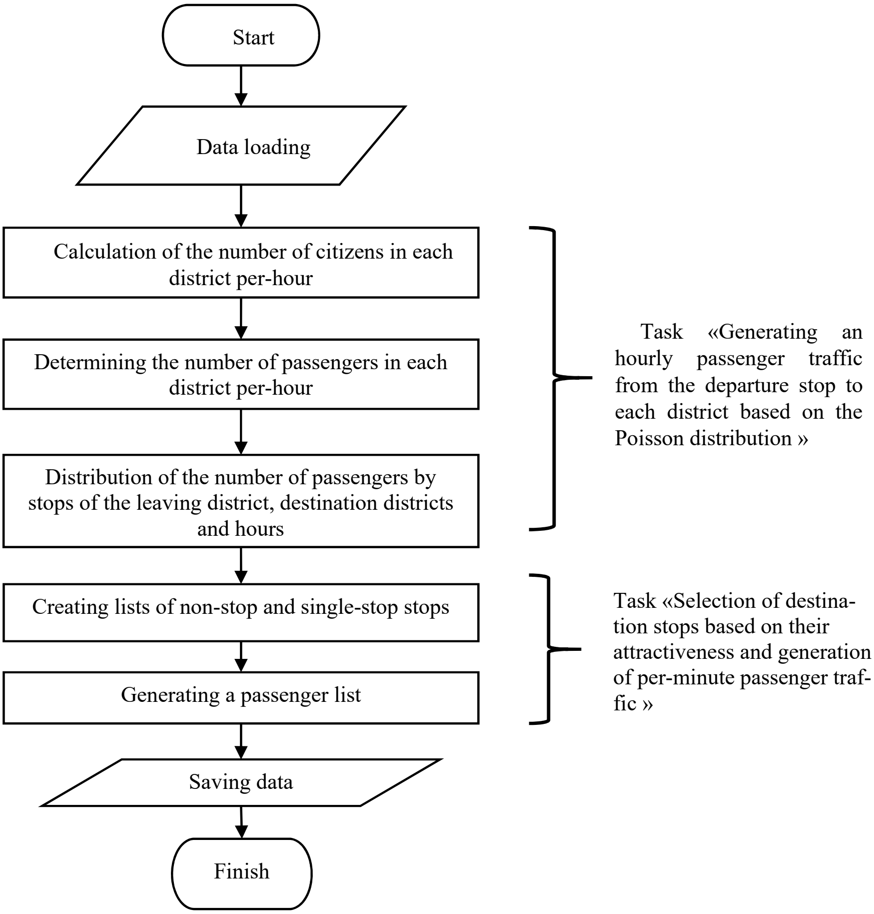

Fig. 1 Algorithm of generating passenger traffic

where i is the district number, h is the hour number, PubT is the proportion of residents who use public transport, RTaxi is the proportion of public transport passengers who prefer minibusses, TripDay is the number of trips per passenger per day, timeDist is the proportion of passengers departing from the i-th district at the h-th hour.

The calculated mathematical expectations are then used in the Poisson distribution.

For the second category (schoolchildren and pensioners), the number of trips per hour differs from (1) by the absence of the Path variable, since it is assumed that schoolchildren and pensioners use only public transport when traveling around the city:

$$\text{y\_HourPens}(i,\ h) = x(i) * (1 - \text{RTaxi}) * \text{TripDay} * \text{timeDist}(i,\ h) \quad (2)$$

Based on the hourly number of trips y_HourWork(i, h) (and y_HourPens(i, h)) and the number of residents living in the vicinity of each PassStop(k) stop, the average number of trips of passengers from a separate k-th stop from the i-th district per h-th hour is determined:

$$\text{matrFlowWork}(k,\ i,\ h) = \text{y\_HourWork}(i,\ h) * \text{PassStop}(k)/\text{PassDist}(i) \tag{3}$$

$$\text{matrFlowPens}(k,\ i,\ h) = \text{y\_HourPens}(i,\ h) * \text{PassStop}(k)/\text{PassDist}(i) \tag{4}$$

where k is the stop number, and PassDist(i) is the number of residents living in the i-th district.

The number of passengers who depart from the k-th stop to the j-th district during the h-th hour (hourly passenger traffic) can be considered a random value of the Poisson distribution. The mathematical expectation of the Poisson distribution λ is related to matrFlowWork(k, i, h) (and matrFlowPens(k, i, h)) and the probabilities of passenger trips between the districts of pRegionsWork (i, j) and pRegionsPens(i, j):

$$\lambda 1 = \text{matrFlowWork}(k,\ i,\ h) * \text{pRegionsWork}(i,\ j) \tag{5}$$

$$\lambda 2 = \text{matrFlowPens}(k,\ i,\ h) * \text{pRegionsPens}(i,\ j) \tag{6}$$

The calculated values of the mathematical expectation are then used in the Poisson distribution.

The random variables of the Poisson distribution specify the number of passengers that depart from a particular stop and are determined separately for each category of passengers, stop, and each hour.

The algorithm for generating random numbers of the Poisson distribution with the mathematical expectation λ is given below (Fig. 2).

Where λ is the mathematical expectation of the Poisson distribution; Random(0, 1) is a uniform random number from the range from 0 to 1; x is the resulting random number of the Poisson distribution.

The Poisson distribution works for a small value of the mathematical expectation. If λ is greater than 30, then the normal distribution is used to generate passengers.

The normal distribution algorithm has the form (Fig. 3).

In Fig. 3 x is the number of passengers who arrived at the stop in one hour, Random (0, 1) is a random number from the range from 0 to 1, including 0.

The values that were generated by the Poisson distribution (generate_puasson) are written to the passenger matrices by category—matrCountPasWork (k, j, h) and matrCountPasPens(k, j, h):

$$\text{matrCountPasWork}(k,\ j,\ h) = \text{generate\_puasson}(\lambda 1) \tag{7}$$

$$\text{matrCountPasPens}(k,\ j,\ h) = \text{generate\_puasson}(\lambda 2) \tag{8}$$

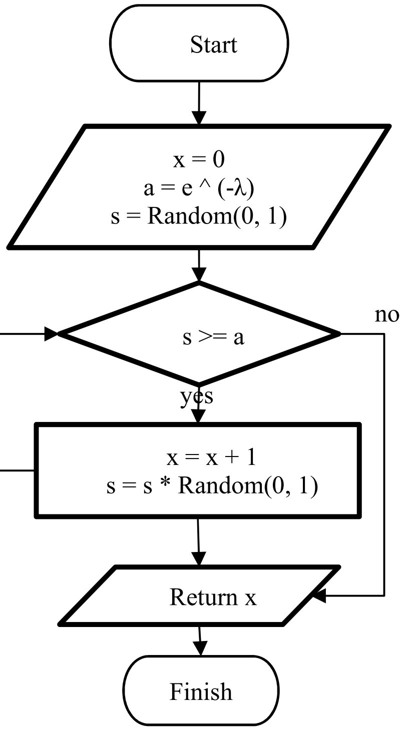

Fig. 2 Poisson distribution algorithm

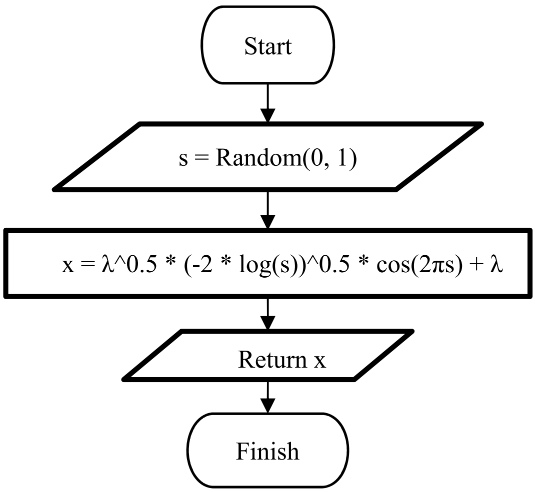

Fig. 3 Normal distribution algorithm

Table 1 Fragment of the results of generating hourly passenger traffic

Leaving stop number	6:00–7:00				7:00–8:00			
	1 Category		2 Category		1 Category		2 Category	
	1 Dist	2 Dist	1 Dist	2 Dist	1 Dist	2 Dist	1 Dist	2 Dist
1 Stop	6	5	24	2	14	3	18	3
2 Stop	0	0	0	0	0	1	0	0
3 Stop	2	4	0	1	0	2	3	1
4 Stop	4	11	2	0	5	3	2	0
5 Stop	3	5	2	2	5	3	2	2
6 Stop	5	18	1	18	4	12	2	23
7 Stop	3	9	1	15	4	5	3	14
8 Stop	4	13	1	18	3	12	0	10
9 Stop	7	11	1	13	4	7	1	17
10 Stop	0	6	1	11	2	8	0	13

The calculated variables matrCountPasWork(k, j, h) and matrCountPasPens (k, j, h) are the results of solving the first task – generating hourly passenger traffic.

Table 1 shows an example of filling in the matrCountPasWork(k, j, h) and matrCountPasPens(k, j, h) matrices. The data is decoded as follows: from 6 to 7 o'clock, 3 workers/students came to the fifth stop for a trip to the first district and 5 workers/students for a trip to the second district.The matrCountPasWork(k, j, h) and matrCountPasPens(k, j, h) matrices will be used to solve the second problem.

Next, the matrCountPasWork(k, j, h) and matrCountPasPens(k, j, h) matrices will be used to generate the per-minute passenger traffic.

Figure 3 shows the total number of passengers who came to all the stops in the city, depending on the hour.

Figure 4 shows that more passengers arrive in the morning (7:00–9:00) when the first category of passengers (workers and students) go to their places of work/study, and in the evening (15:00–17:00), when most of the passengers return home.

6 Generating a Destination Stop

Each passenger that was generated in the first task must be assigned a destination stop and departure time (in minutes). The destination stop depends on the probability of trips between districts, the attractiveness of the stop, and the probability of a non-stop trip (Fig. 1) [17, 18].

The algorithm fills in 2 lists for each stop to take into account the type of trip (with a transfer/ direct flights): a list of stops that can be reached without a transfer, and a list of stops that can be reached with a single transfer. To determine which stop can be reached directly, take the "start" and "end" stops. If they have a common route,

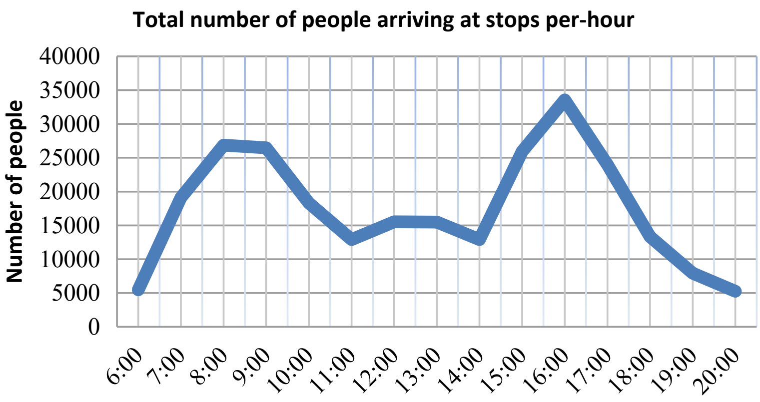

Fig. 4 Graph of the total number of passengers arriving at city stops per-hour

then add the "final" stop to the list of non-stop stops. To determine the stops that can be reached with a single transfer, there is a stop between the two stops that will have the routes of both stops. When such a stop is found, the "final" stop is recorded in the list of stops with one transfer [19, 20].

Each stop has a level of attractiveness that affects the choice of destination stop. The attractiveness of a stop is set by experts in conventional units ranging from 0 (low attractiveness) to 1000 (high attractiveness). The probabilities of choosing arrival stops are shown in Table 2.

The type of stop for a given district is determined using a uniform random number generator: without a transfer, with a single transfer; or a random stop from all stops, whether the district and the attractiveness of the stops are different.

In the case of choosing a stop without a transfer or with a single transfer, the corresponding stops in the destination district are grouped by attractiveness. The destination stop is determined randomly and uniformly, taking into account the probability of selection (Table 2).

The passenger's departure time is selected randomly, evenly over a given hour.

After generating the destination stop and departure time, the matrCountPasWork(k, j, h) and matrCountPasPens(k, j, h) matrices are divided into passengers

Table 2 Probability of choosing destination stops

The border of attractiveness	Probability of selection
from 0 to 100	0,01
from 100 to 250	0,1
from 250 to 400	0,2
from 400 to 600	0,1
from 600 to 1000	0,59

whose number is equal to this value. After that, each passenger is given the generated destination stop and departure time. Next, all passengers are entered in the list, which is the result of solving the second task—selection of destination stops based on their attractiveness and generation of per-minute passenger traffic.

7 Software Implementation

This algorithm is written in C# in the Visual Studio 2019 integrated development environment.

The passenger generation module consists of four blocks: Stop, District, Passenger, and Calculate. These blocks consist of the following elements:

(1) Properties in which data is written in the form of lists (for example, in the «Stop» block, the «CodeStop» property has the values: 1, 2, 3, etc.);
(2) Fields in which both single values and lists and matrices are written (for example, in the «Calculate» block, the «COUNT_HOUR» field (the number of hours in a working day) has the value 15);
(3) Methods that perform some required data processing actions (for example, loading data from a file, generating data, writing data to a file).

The «Stop» block stores all the data about stops, namely:

(1) a stop code;
(2) name of a stop;
(3) a district where the stop is located;
(4) the number of citizens who come to the stop at the place of residence;
(5) the attractiveness of the stop;
(6) a list of route numbers passing through this stop;
(7) lists of stops that can be reached directly or with a single transfer.

The «District» block stores all data about the city's districts:

(1) district code;
(2) name of the district;
(3) the population in a given district by a category;
(4) number of stops in the district (taken from the «Stop» block by comparison: if the name of the district in which the stop is located in the «Stop» block matches the name of the district in the «District» block, then the stop is entered in the list of this district);

The «Calculate» block is designed to load source data from Excel, populate the «Stop» and «District» blocks, generate an hour stream, generate a destination stop, structure the result, and save it to an Excel file. It also sets the following initial conditions:

(1) set as separate values: percentage of citizens using public transport; percentage of public transport passengers who prefer minibusses; the number of passenger trips, depending on their categories; probabilities of choosing a destination stop depending on the attractiveness of the stop; the probability of choosing a stop without a transfer, with a single transfer, or a random choice of a stop;
(2) set in the form of matrices: distribution of passenger movements between districts depending on the time of day and the category of passengers; probability of choosing destination stops.

The «Passenger» block stores the result of solving the second problem the passenger's list. Each passenger in this list has the following parameters:

(1) departure stop code;
(2) passenger departure time (set in minutes from the start of the simulation time—6:00);
(3) destination district code;
(4) destination stop code.

Data from the Passenger class is structured (for each stop) and written to an Excel sheet (Table 3).

Table 3 shows a fragment of data obtained using the described algorithm for generating passenger traffic. Each departure stop has 4 columns: "Passenger"; "Time"; "Destination district"; "Destination stop code". The values in the "Passenger" column show the number of passengers who left this stop. The values in the "Time" column indicate the number of minutes when the passenger appeared at the departure stop from the beginning of the simulation time. The values in the "Destination District" and "Destination Stop Code" columns correspond to the codes of the passenger's destination district and the stop in this district (Table 3).

Table 3 Fragment with the received passenger traffic data

Leaving stops							
1				2			
Passenger	Time	Destination district	Destination stop	Passenger	Time	Destination district	Destination stop
1	17	1	10	1	14	3	7
2	39	8	1	2	55	8	9
3	61	1	10	3	80	1	4
4	62	8	13	4	86	8	1
5	66	8	17	5	89	1	1
6	66	2	14	6	91	1	10
7	74	5	17	7	96	1	4

8 Conclusion

The algorithm was used to model the transport network of a large city. The generated passengers have a good statistical relationship with the available aggregated data on passenger traffic in the considered city [21]. This algorithm will be used by the management organization of the city's transport complex to study passenger traffic and improve the operation of the passenger transport system.

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Society 5.0: Human-Centric Technologies

Synergistic Model of Situational Awareness of the Human Operator

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Abstract The problem of forming models of situational awareness using a synergetic approach is considered. It is noted that situational awareness provides a perception of the current situation and allows you to make the right decisions in response to certain threats. The levels of implementation of situational awareness in the human operator are given. The peculiarity of the first level is the need for joint processing of a large amount of heterogeneous information to identify significant facts and critical information about external objects. The task of the second level is to form a holistic picture of the situation, which is based on existing knowledge and previous experience. The third, highest level of understanding of the situation is based on the person's ability to predict the actions of objects and the consequences of these actions. Two important properties of situational awareness of a human operator are highlighted: associativity and ranking of information depending on the context of the problem being solved. It is proposed to form a model of situational awareness based on Haken's synergetic approach. The process of situation recognition using a synergetic model is described. The value of the attention parameter, which characterizes the importance of a specific characteristic of the state of the controlled object, is noted. The associative properties of the synergetic model and its ability to rank the initial information when controlling the helicopter are investigated.

Keywords Situational awareness · Situational model · Synergetics · Situation recognition · Attention parameter

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1 Introduction

Situational awareness (SA) is the ability of a human operator to perceive heterogeneous information about the environment, analyze it, identify key points and predict their impact on the performance of certain tasks [1–3]. This ability is based on the internal mental models of a person, formed based on the acquired knowledge and previous experience. Due to the complexity of the tasks to be solved, the human operator is required to improve his abilities in mastering situational awareness [4–7].

Different approaches are possible here. It is traditional to improve teaching methods and, consequently, to improve the mental model of a person. However, a person's ability to process large amounts of information, especially in stressful situations, is very limited. In addition, in this case, the objectivity of the formed mental model is largely determined by the intellectual characteristics of a particular person.

Currently, decision support systems help to understand a complex situation [8–11]. Their work is based on knowledge bases of typical situations, which are filled in by experts based on their intuition. However, the main disadvantages of this approach are subjectivism and the degradation of current knowledge in a volatile environment.

Therefore, new approaches to the formation of a situational model as the basis for a formalized representation of situational awareness are needed [12, 13].

2 Levels of Situational Awareness Implementation

In one of the first works devoted to the study of the SA phenomenon, awareness is presented as the result of the analysis of available external information and assessment of the situation, so it includes three components [14, 15]:

- Perception of heterogeneous information and identification of critical factors in the environment;
- Understanding (awareness) of what these factors mean in the context of the implementation of the specified management goals;
- Forecasting the development of the situation and possible consequences.

The peculiarity of the first stage is the need for joint processing of a large volume of heterogeneous information to identify significant facts and critical information about external objects.

The task of the second stage is to form a holistic picture of the situation, including understanding the significance of existing objects and events in the context of the goal (the problem being solved). This understanding of the situation is based on existing knowledge and previous experience.

A distinctive feature of these two stages is the unique ability of a person to rank the initial information according to its significance in the context of the problem being solved. It should be noted here that the result of ranking information depends not only on the existing experience but also on the current psychological state of the person [3, 16].

The third, highest level of understanding of the situation is based on the ability to predict the actions of objects and the consequences of these actions. This ability is achieved through understanding the situation, knowledge of the state, and dynamics of development (behaviour) of elements of the external environment.

An accurate understanding of the situation is based on correctly identifying the elements that determine what needs to be perceived, understood, and projected into the future. This integrated picture forms the central organizing function from which decisions and actions are made.

In practice, an experienced human operator has an internal understanding of the system with which he works—a mental model [17–19]. A well-developed mental model provides:

- Knowledge of the relevant "elements" of the system, which can be used to direct attention and classify information in the process of perception;
- Means of integrating elements to form an understanding of their meaning;
- The mechanism for projecting future states of the system based on its current state and understanding of its dynamics.

During active decision-making, the human operator's perception of the current state of the system can be compared with the corresponding schemas in memory that depict prototypical situations or states of the system model. These prototype situations provide an associative classification and understanding of the situation, as well as a forecast of what may happen in the future [20].

The main advantage of these mechanisms is that the current situation cannot be the same as the one that the human operator has faced before. The matching (pattern recognition) process can be almost instantaneous due to a person's superior ability to match patterns.

When a person has a well-developed mental model of the behaviour of certain systems or areas, he will provide:

- The dynamic direction of attention to critical environmental signals;
- Expectations about future states of the environment (including what to expect as well as what not to expect) based on the projection mechanisms of the models;
- The direct one-step connection between recognized classifications of situations and typical actions ensures very rapid decision-making.

3 Formation of a Situational Awareness Model Based on Haken Synergetic Approach

Let's highlight two fundamentally important properties of situational awareness:

- Associativity, i.e., the ability to form a holistic view of the situation from its fragments;
- The ranking of information depends on the context of the problem being solved.

Some neural networks have the property of associativity, for example, the Hopfield network [21, 22]. It is a single-layer neural network with feedback and belongs to the class of so-called relaxation neural networks. In the process of operation, the dynamics of the network converge to one of the equilibrium positions, which are determined in advance in the learning process, and information about them is stored in the matrix of connections.

Equilibrium positions (attractors) are local minima of a function called the energy of the network. As a result, the Hopfield network can recognize the presented distorted image, for example, with superimposed noise or containing only an important part of the original image. This is the manifestation of its associative properties.

However, the Hopfield network has several disadvantages:

- The network has a relatively small amount of memory (approximately 15% of the number of neurons in the Hopfield layer);
- The number of false results increases (the network can converge to false attractors) with the growth of the network dimension;
- Information is not ranked during training.

These disadvantages do not allow the Hopfield network to be applied to form a situational awareness model, although the network has associative properties.

In this regard, it seems promising to use the synergetic theory of Haken in the formation of a model of situational awareness. As in most other intellectual systems, Haken synergetic model includes learning and recognition processes [23–25].

A distinctive feature of the Haken approach is that during the learning process, a potential function V is formed in n-dimensional space with many areas of attraction (attractors). This function defines the structure of the potential distribution field. A feature of the structure of the potential field is the set of local minima, the coordinates of which are determined by etalons. There is no global minimum.

The process of recognizing a situation by a vector of features q is described by a differential equation

$$\dot{q} = -\frac{\partial V}{\partial q}$$

and is reduced to solving it for given initial conditions $q(0) = q_0$.

These initial conditions represent the initial pattern of the identifiable situation, and the solution is the pattern ν of the etalon situation.

Haken justified the representation of a potential function in the form:

$$V = \frac{1}{2}\sum_{k=1}^{M}\left(q^{+}v_k\right)^2 + \frac{B+C}{4}\left(\sum_{k=1}^{M}\left(q^{+}v_k\right)^2\right) - \frac{B}{4}\sum_{k=1}^{M}\left(q^{+}v_k\right)^4.$$

Here q^{+} is the associated vector and it satisfies the equation

$$q^{+}v_k = v_k^{+}q, k = 1, \ldots, M.$$

In this case, the dynamic system for recognizing and classifying the situation based on the fixed feature vector q has the form:

$$\dot{q} = \sum_{k=1}^{M}\lambda_k\left(v_k^{+}q\right)v_k - B\sum_{k'\neq k}^{M}\sum_{k\neq k'}^{M}\left(v_{k'}^{+}q\right)^2\left(v_k^{+}q\right)v_k - C\left(q^{+}q\right)q, \quad (1)$$

where B and C are constants; λ_k is the attention parameter of the k-th etalon pattern; M is the number of etalons. A pattern can only be recognized if its attention parameter is positive, and the convergence rate of pattern recognition is controlled by λ_k, B and C.

Thus, the process of recognizing the initial image (pattern) can be specified as follows: for a given test pattern q0, the dynamics of the system (1) transfers the initial unknown state $q(0) = q_0$ through intermediate states q(t) into one of the etalon patterns (states) vk, i.e.

$$q(0) \rightarrow q(t) \rightarrow v_k, 1 \leq k \leq M.$$

The initial situational state vector differs from its prototype (etalon) and can contain only its fragments, but due to the properties of the potential function V, the prototype will be restored completely. This is how the associativity property is realized.

The attention parameter λ_k affects the shape of the attractor, making its slopes either flatter or steeper. This allows you to highlight more relevant information in this context. Thus, by setting a priori different values of the attention parameter for different values of k, it is possible to rank information according to its significance for a given task.

The synergetic model allows not only to reconstruct the image (situation) from its fragment but also to solve the classification problem.

Using the variable substitution $\xi_k = v_k^{+}q$ in (1), Haken obtained the equation

$$\frac{d\xi_k(t)}{dt} = \lambda_k\xi_k - B\xi_k\sum_{i\neq k}^{M}\xi_i^2 - C\xi_k\sum_{i=1}^{M}\xi_i^2. \quad (2)$$

The variable $\xi_k = v_k^+ q$ is called the "order parameter".

Equation (2) is used to classify patterns. For the currently tested vector q0, its order parameter $\xi_k(0) = v_k^+ q_0$ is calculated. Here v_k^+ is the conjugate vector. The value $\xi_k(0)$ is the initial condition for solving Eq. (2). If the obtained solution ξ_m has the maximum value, then the initial image is closer to the etalon v_m.

4 Example of Using a Synergetic Model

Let us evaluate the associative properties of the synergetic model and its ability to rank the initial information in the process of threat analysis when controlling a helicopter.

During the flight, there may be threats that affect the quality of the flight mission. These threats can be divided into three categories:

- Threats affecting the quality of the assignment (category 1);
- Threats to the integrity of the helicopter, which are characterized by the time sufficient for the crew to understand the situation (category 2);
- Threats to the integrity of the helicopter, which are characterized by time insufficient for the crew to understand the situation (category 3).

Each category has its etalon vector.

Let's introduce the characteristics of the state (situational awareness) (Table 1). Etalon vectors are also shown in the table. The prototype vectors were selected by experts based on their experience and common-sense logic.

Let's identify the category of threats defined by the current situational vector q0. Let's assume that all parameters of attention are equal to one.

Then for the current tested vector

$$q = [0, 1, 1, 1, 0, 1, 1, 1, 1, 1, 0],$$

it is necessary to calculate its order parameters:

$$x_1 = -0.7438; x_2 = 1.6529; x_3 = 0.7438.$$

The second-order parameter has the maximum value. Therefore, the tested vector q corresponds to the class that defines the etalon ν_2.

To estimate the similarity of the recognized vector and the selected prototype, we introduce the following similarity coefficient:

$$\mu_k = \frac{\sum_{i=1}^{n} \nu_k(i) q(i)}{\sqrt{\sum_{i=1}^{n} \nu_k(i)^2 \sum_{i=1}^{n} q(i)^2}}.$$

Table 1 State characteristics and prototype vectors

No.	State characteristics	Current vector q_0	Prototype vector v_1	Prototype vector v_2	Prototype vector v_3
1	Engine failure	0	0	0	1
2	Interruptions in operation	1	1	1	0
3	Knocks in the engine	1	1	1	0
4	Increased vibration of the helicopter	1	1	1	0
5	Permissible oil temperature in the gearbox	0	1	1	0
6	Failure of the main control drive for steering surfaces	1	0	0	1
7	Failure of the backup control drive for steering surfaces	1	0	1	1
8	Failure of the satellite navigation system	1	1	1	1
9	Failure of the inertial navigation system	1	0	1	1
10	Low visibility	1	0	0	1
11	Good visibility	0	1	1	0

Here v_i(k) is the k-th component of i-th etalon, and $q(k)$ is the k-th component of the tested situational vector.

In this case, the following values of the coefficients are obtained: $\mu_1 = 0, 78$; $\mu_2 = 0, 8$; $\mu_3 = 0, 67$.

Thus, the tested vector has the greatest similarity with the etalon v_2. The current situation, given by the vector q, corresponds to the second category.

Let's determine the effect of the attention parameter on the result of recognizing the situation.

The attention parameter describes the importance of a particular state characteristic. In the given case, it is determined by the estimate of the time that the crew needs to make a decision, as well as the significance of the possible consequences when

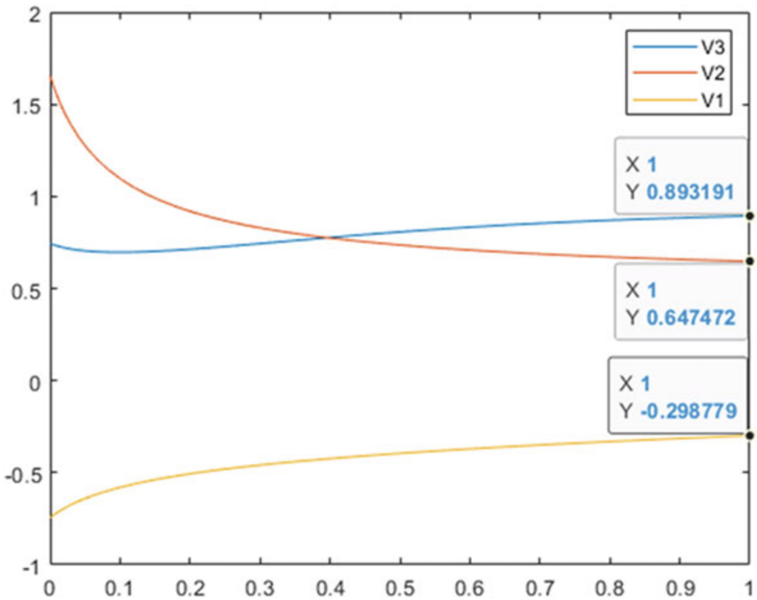

Fig. 1 Solution of the differential equation with the specified attention parameters

this characteristic occurs. Therefore, we will assume that the less time is allotted to the crew for making a decision, the greater the attention parameter should be.

Consider a situation where the attention parameters are set as follows:

$$\lambda_1 = 1, \lambda_2 = 2, \lambda_3 = 3.$$

This distribution of attention parameters by categories is formed taking into account the table and based on common sense. The transients of establishing the order parameters obtained in the process of solving Eq. (2) are shown in Fig. 1.

Here, the current values of the order parameters are plotted on the Y-axis, and the current time is plotted on the X-axis. The colour indicates the corresponding categories.

Figure 1 shows that taking into account the attention parameter in the process of transforming the initial pattern, the situation will be classified as category 3. This is because the initial vector takes into account a sufficiently large number of threats, as well as the absence of the state characteristic “Permissible oil temperature in the gearbox”, which requires the value of the attention parameter $\lambda = 3$.

5 Conclusion

Situational awareness provides a perception of the current situation and allows you to make the right decisions in response to certain threats. SA is based on the mental models of the human operator. Their adequacy depends on many subjective characteristics (factors) inherent in a person, for example, his intellect, psychical state. The mathematical formalization of SA allows reducing the subjective component in the formation of situational awareness. The synergetic Haken processor is used as the mathematical basis for the formation of the mathematical model of situational awareness.

The example shows the possibility of classifying the situational vector by the degree of possible threats to the assignment, as well as the effect of ranking information by its significance in a specific task.

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Formation of Situational Awareness Based on Mental Models in the Controlling Complex Technical Objects

L. T. Zaw and S. I. Suyatinov

Abstract The problem of assessing the situation in the control of anthropocentric objects using situational awareness models is considered. In general, the term "situational awareness" is used to describe the degree of adequate assessment of external and internal factors that affect the decision-making of a human operator in the process of controlling a complex object. This problem is not easy due to the complexity and the large number of factors that need to be taken into account to make effective decisions. As a result, situational awareness in the control of anthropocentric objects has a hierarchical structure. The levels of formation of situational awareness in the human operator are given. The place of the situational awareness model in the control system is noted and the relationship of the situation models with human mental models is analyzed. An approach to the formation of situational awareness based on biological principles of constructing mental models and taking into account the functional state of a human operator is proposed.

Keywords Human operator · Anthropocentric objects · Situational awareness · Situational models · Mental models

1 Introduction

The increasing complexity of modern technical systems and also the tasks of controlling their states have increased the responsibility of the human operator [1–5]. An analysis of the operators' activities in these conditions shows that the decisions are made in accordance with the principles of situational management. Therefore,

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as a basis for creating automatic systems and improving the efficiency of automated systems for controlling the states of complex technical objects, it is necessary to consider situational models of the controlled system state that correspond to the conditions of functioning and control goals [6–10]. Situational models are a formalized representation of situational awareness.

The task of forming situational awareness (SA) arises in many subject areas, including aviation, air traffic control, shipping, healthcare, emergency response, nuclear power plant management, etc. [11–14]. Moreover, insufficient or inadequate awareness of the situation is one of the main factors in accidents associated with human error [15, 16].

Thus, the need for full-scale control of the situation exists in areas where there is a large volume of information flow and a sufficiently high degree of risk, i.e., where a bad decision can have serious consequences.

The purpose of this chapter is to study the process of forming situational awareness for the control of anthropocentric objects. Such objects are complex systems, including onboard measuring and actuating devices, an advanced onboard digital computing system, the crew and its cockpit with a modern information and control field. In such human–machine objects, the responsibility for control is assigned to the human operator. These include, for example, aviation and space technology.

The considered problem is not easy due to the complexity and the large number of factors that must be taken into account in order to make effective decisions. In particular, SA does not end with the simple perception of the data. Situational awareness also depends on a deeper understanding of the meaning and significance of this data. Together, this implies an understanding of how the components of the environment function and interact, as well as the ability to predict future states of the system.

2 Situational Awareness Concept

In the general case, the term "situational awareness" is used to describe the degree of adequate assessment of external and internal factors that influence decision-making by a human operator in the process of controlling a complex object. This circumstance necessitates the acquisition of knowledge and the formalization of the properties of the situational model. Currently, such functions are performed by experts based on their own intuition. However, in relation to the control of anthropocentric objects, this approach is ineffective. Its main disadvantages are subjectivity and degradation of current knowledge in a changing environment. Therefore, new approaches to the formation of situational models are needed as the basis for the formalized presentation of SA [17, 18].

Situational awareness in the control of anthropocentric objects has a hierarchical structure and includes the following levels (Fig. 1):

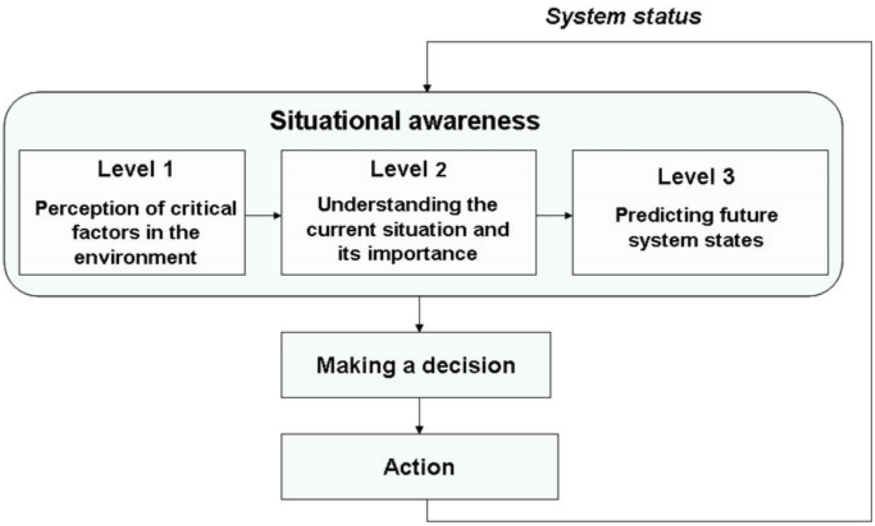

Fig. 1 Place of the situational awareness model in the control system

- Perception of critical factors in the environment (Level 1);
- Understanding what these factors mean, especially when they are combined in relation to the flight crew's objectives (Level 2);
- And at the highest level, an understanding of what will happen to the system in the near future (Level 3).

Levels 2 and 3, as higher levels of situational awareness, allow a person not only to effectively manage a complex object but also to make the necessary decisions in a timely manner.

Situational awareness is an important part of the control of modern aircraft, and high SA levels are required to achieve successful results in aviation. In order to fly in a dynamic flight environment, the flight crew must not only know how to operate the aircraft and the proper tactics, procedures, and flight rules but must also have an accurate and up-to-date picture of the aircraft's state and the environment [19, 20].

In accordance with the hierarchy presented, at Level 1, the pilot must perceive such important elements as other aircrafts, terrain, system status, and signal lights, and their respective characteristics. At level 2, the human operator forms a holistic picture of the environment, including an understanding of the significance of objects and events. And at level 3, the future actions of elements in the environment are predicted so that the pilot can choose the most favorable course of action to achieve the control objectives.

Thus, it can be argued that the level of situational awareness is largely determined by the knowledge, practical experience, and formed competencies of the human operator (in this case, the pilot). And all this is embodied in his mental model.

3 The Relationship Between the Mental Model and the Situation Models

The mental model is an internal conceptual representation of the causal relationships between the elements that people use to understand and manipulate reality [21–23]. Mental models can determine:

1. What information is accessed,
2. How this information is interpreted and integrated,
3. What forecasts are made in relation to the system in the near future (in fact, these are all three main levels of awareness of the situation).

In this sense, the situation model is the current implementation of the mental model, which is more general in nature. A pilot is considered situationally aware when he has a good general mental picture of what is happening during the flight, and it consists of a set of models of situations formed by a person in the process of training and life experience.

The following is an approach based on the use of biological principles of presenting situational awareness [24]:

- Availability of a multi-channel information system (sensor fields) for monitoring the external environment and the internal state of the system;
- Principle of multiscale representation of a virtual model: the behavior program (control model) has a hierarchical structure containing consistent submodels of varying degrees of detail and abstract representation (a set of situational models);
- Interaction of models of different levels on the principles of regularization;
- Multi-model reflection of the outside world;
- Principle of invariant representation of the external environment;
- Availability of mechanisms for forecasting changes in the external world.

The basis of these principles is precisely the mental models. The hierarchical structure of the mental model, which includes a set of models of situations, is shown in Fig. 2.

Note, that mental models are not immutable, they can grow and develop with experience. However, to a large extent, mental models represent static knowledge about the system: its important features, how it functions, how different components affect others, and how its components will behave when faced with different factors and influences. And in this respect, the production rules of expert systems are actually the implementation of the mental models of the expert.

The above scheme of SA formation, based on the mental model, does not take into account the fact that the loss of situational awareness and also the risk of flight safety can be caused by other factors, such as fatigue, stress and high workload. A loss of understanding about any of these factors can lead to a loss of the pilot's overall situational awareness. Therefore, it is also necessary to monitor the state of the person and his performance.

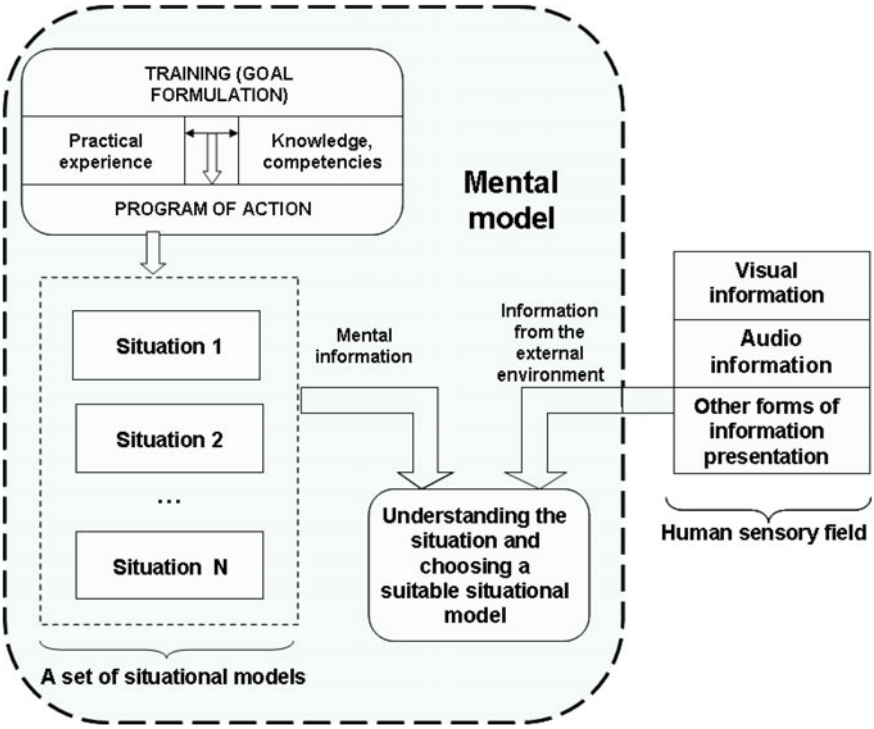

Fig. 2 Scheme of the formation of SA based on the mental model

To implement the proposed approach, it is necessary to develop methods for systematization and formation of adaptable situational models devoid of subjectivity, based on the biological principles of constructing mental models and taking into account the functional state of the human operator [4, 24, 25].

The general structure of the automated control system for anthropocentric objects is shown in Fig. 3.

Thus, the general structure of the decision support subsystem for controlling anthropocentric objects should include three important modules. Their joint functioning will make it possible to form a situational awareness taking into account the state of the human operator and a set of unstructured data about the external environment and the state of the controlled object.

Let's consider a possible way to implement the monitoring module.

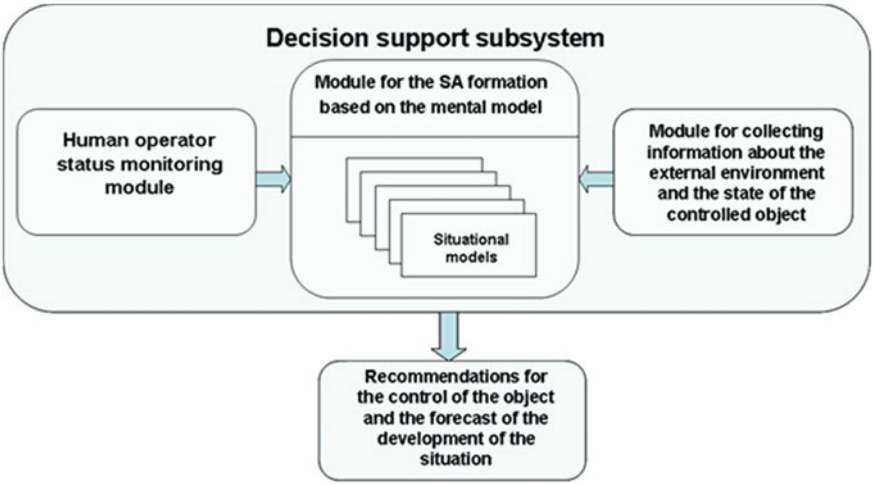

Fig. 3 General structure of the automated control system

4 Features of Assessing the State of a Human Operator

Currently, there are various methods for assessing the state of a human operator: by galvanic skin response, by biometric images, by the frequency-amplitude spectrum of EEG signals (electroencephalogram), by heart rate variability. Among them, one of the most objective and convenient for automated processing is the assessment of the functional state by biosignals (ECG, sphygmogram, etc.). At the same time, the use of two biosignals of the cardiac cycle increases the reliability of the assessment, which also solves the problem of identifying the cardiovascular system.

The result of identification is a model of the dynamics of the system, and the state is assessed according to the values of the parameters of the model [4]. However, the problem is that the parameters characterizing the same states may have different meanings for different people. This is due to the variety of psycho-physiological types of people and their different reactions to stress and fatigue.

To solve this problem and to implement the module for monitoring the state of a human operator, a two-level information processing scheme is proposed. The structure of the system for assessing a person's state based on biosignals and the results of psychological testing is shown in Fig. 4.

The upper level determines the "semantic" model or psycho-physiological type of human behavior based on the initial information (psychological testing of people). At the lower level, a dynamic model of the state of the cardiovascular system is created based on biosignals. Then, in the information merge block, the current state of a person is determined for the selected psychophysiological type of behavior and the parameters of the model obtained in the lower block.

In this case, the model merging mechanism is the solution to the classification problem. Each class has its own set of parameters of dynamic low-level models that

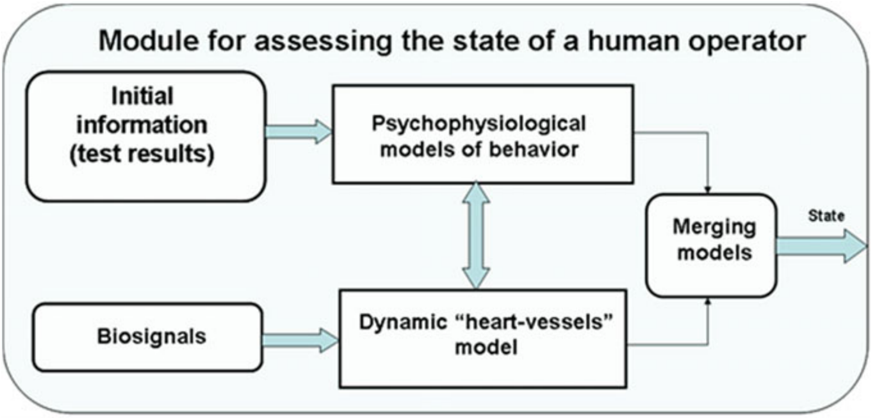

Fig. 4 Two-level system for assessing the human state

determine a particular state of a person. The specific state is defined in the behavior merge block.

Thus, we obtain the following procedure for assessing the state [25]. According to the results of psycho-physiological testing at the upper level, the psychological image (model) of a person is determined. In the testing process, such indicators are assessed as:

- The severity of emotional stress (maximum, severe, moderate, absent);
- Balance of nervous processes (excitement, inhibition, norm);
- Strength of nervous processes (weak, medium, strong);
- Decreased performance (high, moderate, absent);
- Social adaptation according to the Holmes scale (low, threshold, high);
- Toronto scale of alexithymia (neuroses, psychosomatic diseases, healthy);
- Age (20–35 and 36–50).

In the memory of this level, for each psychological image, the sets of parameters of the lower-level model, that characterize the functional state, are stored.

At the lower level, the system dynamics model is reconstructed using biosignals. The parameters of the resulting model are a vector of features of the functional state.

In the merge block, a set of parameters of a certain psycho-physiological image is mapped to this vector. Thus, when assessing the state of a human operator, its psycho-physiological type is taken into account. This reduces the ranges of possible variations of parameters in the gradation of functional states. As a result, the objectivity of the assessment is increased.

Note that physically the upper level and the merge block can be implemented using intelligent technologies, for example, in the form of expert systems.

5 Conclusion

The chapter focuses on the process of forming situational awareness in a human operator who controls a complex anthropocentric object. Taking into account the peculiarities of this process, the general structure of the automated control system is proposed. It takes into account the principles of constructing mental models and the functional state of the human operator. To increase the objectivity of decisions, a two-level procedure for assessing a person's state is used.

The obtained results, based on the biological principles of the formation of situational awareness, are of a system-wide nature and can be used in automated and automatic systems in order to increase the autonomy of control. They can serve as a conceptual basis for the construction of applied systems using the elements of intelligent control inherent in living organisms.

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Methods and Technologies of Developing Computer Simulators for Training Resource-Saving Control of Electrotechnological Installations

Olga Ershova and Tamara Chistyakova

Abstract Methods and technologies for the development of computer simulators for the training of control industry personnel and the acquisition of skills in resource-saving control of electrotechnological installations, characterized by a variety of processes and the simultaneous occurrence of chemical reactions and phase transformations, are considered. A unified functional structure of simulators, information, mathematics, and software was created, which is a flexible customizable environment for this class of objects. Based on the information and mathematical support, training scenarios are developed in which different situations and disturbances are modeled by changing the model coefficients and varying the values of variables in the ranges of change. To develop interfaces as close as possible to real objects in a limited time frame, a SCADA HMI was used. The methodology for the development of computer simulators has been tested on the example of electrochemical and electrothermal production of aluminum, calcium carbide, and phosphorus. The efficiency of computer simulators is confirmed by the results of approbation for Russian industrial enterprises, scientific and educational organizations.

Keywords Computer simulators · Training of control industry personnel · Resource-saving control · Electrotechnological installations

1 Introduction

Modern chemical production facilities are characterized by a combination of the complex hardware design of technological processes (TP) and control systems, increasing the efficiency of which is associated with improving the systems themselves and improving the skills of production personnel of various categories who

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operate the equipment and make control decisions. It is generally recognized that the training and retraining of qualified personnel are effectively carried out using modern training tools and information technologies. To do this, we need training centers equipped with software and hardware complexes, including computer simulators (CS) [1–5].

The object of research of this work is electrotechnological installations (EI), which are installations in which electrical energy is converted into other types of energy with the simultaneous execution of TP. The term "electrotechnological installations" includes units in which electrotechnological processes are carried out, including the processes of electrochemical and electrothermal production, which have common features: potentially dangerous, material- and energy-intensive, characterized by a variety of processes and a large number of interdependent parameters, chemical reactions occur under the influence of high temperatures due to electric heating, chemical and phase transformations occur simultaneously in the reaction zone, control actions are used to maintain the TP, which differ in the degree of influence and frequency of application [6–8].

Since the objects under consideration are energy-intensive, resource-saving control is necessary, and since the objects are complex, characterized by a significant influence of disturbing influences, simulators are needed.

The presence of common features of the objects of study and control made it advisable to create a single functional structure of simulators. A methodology for developing CS is proposed to improve the efficiency of the operation of plants by acquiring control skills by personnel that ensures safe, resource-saving operating modes while ensuring the specified performance and the required quality of the target products.

The safe operation of the TP is due to strict compliance with the technology, the ranges of parameters provided for in the technical regulations, and the equipment with effective means of control, regulation, and emergency protection.

Energy-saving—this is a set of various research, educational, design, production and economic, organizational and economic, managerial and any business activities carried out on the basis of the most complete use of intellectual and information resources, to ensure optimal unit costs of all types of natural and material resources (mineral raw materials, fuel, and energy resources, water, air), as well as labor resources, which are necessary for the release in the required place at the required time of the required type of the required quality and quantity of products in compliance with the conditions of national and international legislation, as well as the requirements for environmental protection from chemical pollution [9–16].

2 Formalized Description of the Objects of Study and Control

The system approach to the object of study consists of a comprehensive study of processes as a whole from the standpoint of system analysis, consideration of a complex problem and its detail, formulation of criteria for specifying goals, synthesis of an effective functional structure for achieving goals, development of information, mathematical and software.

The prospects for the creation and implementation of CS are high-quality training of operational personnel in order to study the features of production: the structure and connections of equipment, operating disturbances, control restrictions, cause-and-effect relationships in the control object, the ability to analyze information about the state of the object in a timely manner to make the right control decisions.

Trends in the development of industry and information technology place high demands on the development and creation time of software, for which it is necessary to use developed development environments that allow you to create interfaces for control personnel, as close as possible to real objects and in a limited time. The development of simulator software in the SCADA system environment allows you to effectively solve these problems.

In this chapter, we propose an approach to the development of computer simulators in the SCADA environment for the acquisition of professional competencies by personnel in the control of electrical technology installations.

Taking into account the common features of the EI, a single structure of simulator software for this class of objects has been created. Software development in the environment of SCADA systems is an urgent science-intensive task on the way to improving the reliability, security, and efficiency of their operation, which has practical value. Modern technologies can significantly reduce the development time, which confirms the correctness of the chosen approach [17].

Based on the analysis of EI as objects of study and control and their general characteristics and for the synthesis of the general structure of the software, a formalized description of the processes presented in Fig. 1 is developed, the tasks of training and control are formulated, information, mathematical and software are developed.

ID–process ID: ID = 1–aluminum production, ID = 2–production of calcium carbide, ID = 3–phosphorus production;

$\overline{x}^{ID}$–input variables: $X^{ID}_{material}$–characteristics of raw materials (specific consumption of raw materials, concentration of the i-th chemical component in the s-th input stream, density, granulometric composition of the s-th input stream); $X^{ID}_{construction}$–design characteristics of the electrotechnological installation (diameter\length and width of the EI, height, diameter of the electrode /anode); $X^{ID}_{electrical}$–electrical parameters of the installation; I–current strength, A.

$\overline{\mu}^{ID}$–control actions: ΔG^{ID}_{mix}–raw material consumption, t/h; $\Delta l^{ID}_{electrode}$–position of the electrodes (anodes), m;

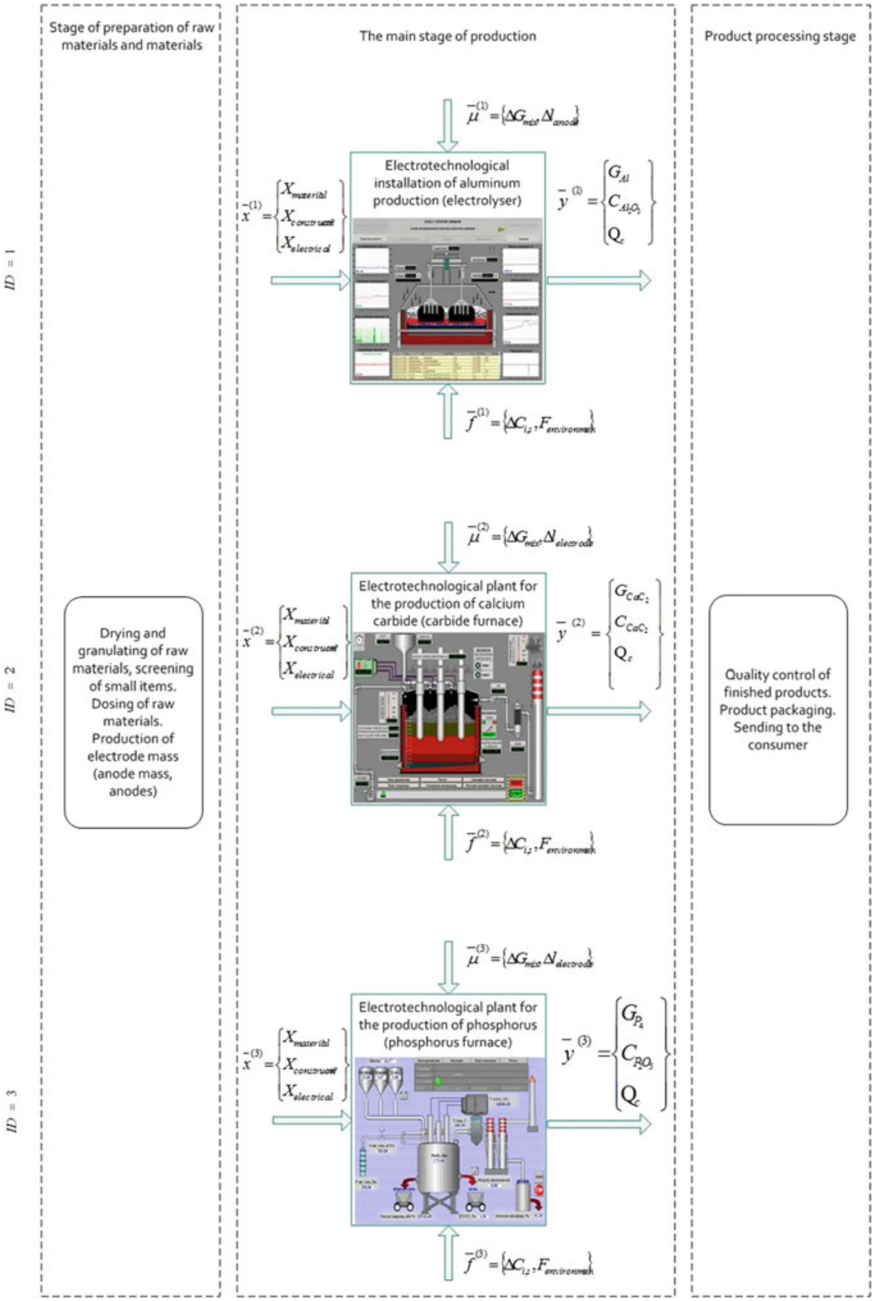

Fig. 1 Formalized description of the objects of study and control

$\overline{f}^{ID}$–disturbing effects: $\Delta C_{i,s}^{ID}$–fluctuations in the chemical composition of the i-th component in the s-th input stream of raw materials; $F_{environment}^{ID}$–fluctuations in environmental parameters (temperature, humidity);

$\overline{y}^{ID}$–output indicators: $G_{product}^{ID}$–quantity of the received product, kg/s;

$C_{product}^{ID}$–concentration of the key component in the melt, mass fraction;

Q_c^{ID}–the amount of electricity consumed for the production of products, Wh.

3 Information and Mathematical Support

Information support includes:

- Database (DB) of administrative and production personnel, which stores information about all registered users with the appropriate access rights: the administrator ensures the operation of the system; the instructor organizes the training process; the trainees are the main users.
- Database of TP variables;
- The database of raw materials includes the type of raw materials of a certain field, the density of raw components, the decomposition coefficients of the components, and stoichiometric coefficients;
- The equipment database includes the types of EI, design characteristics, current strength, and coefficients that determine the type and design features of the EI;
- Database of products of various brands.

The knowledge base (KB) for emergency control is developed based on expert knowledge and data on the operation of the facility and contains information about typical emergency situations, the causes of their occurrence, and recommendations for elimination. Classification of situations in the KB is carried out by a combination of DB variables that describe each situation. DB and KB can be updated and supplemented as necessary [18].

The mathematical software includes mathematical models (MM) of processes. The task of MM synthesis is to determine the structure and ensure acceptable accuracy by adjusting the coefficients of the model [18, 19], the functional relations of which are presented in the form $\overline{y} = \phi(\overline{x}, \overline{\mu}, \overline{A})$, where A is the coefficients of the model.

The generalized model for the objects of study and control can be represented like this.

Material balance equation for calculating the concentration of a key component of raw materials C_s in the melt (reaction zone):

$$m_{raspl} \cdot \frac{d_s}{dt} = \Delta G_{mix} - k_r \cdot G_{product} \quad (1)$$

where $G_{product}$–the amount of the resulting product, kg/s.

$$G_{product} = k_{elchem} \cdot I \cdot \eta \quad (2)$$

k_{elchem}–the electrochemical equivalent of the key component, kg/(A·s); I–current strength,

A; η–current output; m_{raspl}–melt mass, kg; ΔG_{mix}–consumption of loaded raw materials, kg/ s;

k_r- stoichiometric coefficient of decomposition reaction; $C_{product} = f_1 (C_s)$ [6].

The initial data for the calculation (1) are m_{raspl}, G_s, k_r.

Equation for calculating the inter-pole distance l_{mpr}:

$$\frac{dl_{mpr}}{dt} = v_{el} - v_{product}, \quad (3)$$

where $v_{el} = \frac{G_{el}}{\rho_{el} \cdot S_{el}}$–the rate of combustion of the electrodes/anodes due to their consumption, m/s.

$$v_{product} = \frac{G_{product}}{\rho_{product} \cdot S_{raspl}}$$-product level change rate, m/s.

where G_{el}–consumption of electrodes/anodes, kg/s; ρ_{el}–density of electrodes/anodes, kg/m^3; S_{el}–cross-sectional area of the electrodes/anodes, m^2 ; $\rho_{product}$–product density, kg/m^3; S_{raspl}–melt cross-sectional area, m^2 .

The initial data for the calculation (3) are: $G_{product}$, G_{el}., S_{el}, S_{raspl}.

Heat balance equation for determining the melt temperature:

$$m_{raspl} \cdot c_{raspl} \cdot \frac{dT_{raspl}}{dt} = I^2 \cdot R_{mpr} - \alpha_{raspl} \cdot S_{raspl} \cdot (T_{raspl} - T_{smelt}) - k_{bottom} \cdot S_{bottom} \cdot (T_{raspl} - T_0) \quad (4)$$

where c_{raspl}–heat capacity of the melt, J/(mol K); T_{raspl}–melt temperature, °C; R_{mpr}–melt resistance, Ohm; α_{raspl}–heat transfer coefficient from the melt to the melting zone, W/m2 °C; S_{raspl}–melt cross-sectional area, m2; T_{smelt}–the temperature in the melting zone, °C; k_{botton}–heat transfer coefficient from the melting zone to the environment, W/m2°C; S_{botton}–total area of the spring and electrodes/anodes, m2; T_o–ambient temperature, °C.

The equation for calculating the speed of movement of electrodes/anodes:

$$\frac{d\Delta l_{el}}{dt} = v_{el} - v_{product} + K_{ctrl} l_{ctrl} \quad (5)$$

where l_{ctrl}–speed of movement of the electrode/anode during control, m/s; K_{ctrl}–accepts values −1, 0, + 1.

The voltage at the installation and the current passing through it are available for automatic control. These parameters are related to the state variables of the installation via resistance and reverse EMF, from which it is possible to obtain an explicit dependence of the voltage on the state variables. Therefore, the equations for calculating the electrical parameters:

$$U = I \cdot R + E \tag{6}$$

$$R = R_{nom} + k_{R_l} \cdot (l_{mpr} - l_{mpr_{nom}}) - k_{R_T} \cdot (T_{raspl} - T_{raspl_{nom}}) + k_{R_C}(C_S - C_{S_{nom}}),$$
$$E = E_{nom} - k_{E_T} \cdot (T_{raspl} - T_{raspl_{nom}}) - k_{E_C} \cdot \ln \frac{C_S}{C_{S_{nom}}},$$

where U–operating voltage, V;

R–resistance, Ohm;

E–reverse EMF, V;

index nom–nominal values;

k_{Rl}, k_{RT}, k_{Rc}, k_{ET}, k_{Ec}–coefficients of influence of the type and design features of the equipment on the electrical parameters.

Initial conditions for solving a system of equations:

$$t_0 = 0; \quad C_S(t_0) = C_{S_0}; \quad T_{raspl}(t_0) = T_{raspl\,0}; \quad \Delta l_{el}(t_0) = \Delta l_{el\,0}; \quad t_0 \le t \le t_k.$$

Calculation of the amount of electricity consumed Q_c for the production of the product:

$$Qc = J2\,R\,t,$$

Thus, taking into account the Eqs. (1)–(6) $Q_c = f_2(J, R, T_{raspl}, C_s, \Delta G_{mix}, \Delta l_{el})$ and by changing the values of the control actions, you can minimize the value Q_c.

The results of the calculation of the models were verified according to the experimental data provided by "GIPROCHIM-TECHNOLOG" S.Ltd and "RUSAL-VAMI" Ltd, and their adequacy was confirmed by the fulfillment of the adequacy condition according to the Fisher criterion.

In the normal mode, the task of management is to find such values of control actions that ensure the maintenance of the routine resource-saving mode and the required values of production indicators (productivity and quality of the target product) when the object is affected by disturbing influences and while observing the restrictions on the values of variables).

Setting the task of teaching resource-saving control: for a given vector of input variables X^{ID} under the influence of disturbances f^{ID} by varying the values of the control actions μ^{ID} in the regulatory ranges $\{\Delta l^{ID}min \leq \Delta lID \leq \Delta l^{ID} max, \Delta G^{ID}min \leq \Delta G^{ID} \leq \Delta G^{IDI}max\}$, depending on the types of equipment and raw materials, find such a vector of control actions $\mu^{ID}opt = \{\Delta G^{ID}opt, \Delta l^{ID}opt\}$, at which the required performance is provided ($G^{ID}{}_{product}min \leq GID_{product} \leq GID_{product}max$) and the specified quality ($C^{ID}{}_{product}min \leq C^{ID}{}_{product} \leq C^{ID}{}_{product}max$) of output product, the minimum amount of electricity consumed $Q_c$min, under the restrictions on safety indicators $l^{ID}{}_{electrode} \leq l^{ID}{}_{доп}$, $T_{smelt} \leq T_{raspl} \leq T_{raspl}$ max.

Setting the task of teaching control in emergency situations: for a given vector of input variables X^{ID} based on the description of abnormal situations associated with the release of safety indicators and equipment performance beyond acceptable limits, the causes of their occurrence, determine the most likely cause of the situation, as well as the magnitude and direction of changes in control actions μ^{ID}, which will ensure the exit of the object from the mode of violation of the regulatory boundaries of variable values and their return to the acceptable range of operation.

Based on the information and mathematical support, training scenarios are developed in which different situations and disturbances are modeled by changing the model coefficients and varying the values of variables in the ranges of change.

When solving the problem of learning to control an object with different sources of raw materials [20], the vector of coefficients A $\{k_{elchem}, k_r, G_{el}, \rho_{el}\}$.

When solving the problem of learning to control various types of EI [21], the vector of coefficients A $\{\eta, J, k_{Rl}, k_{RT}, k_{Rc}, k_{ET}, k_{Ec}\}$.

Scenarios have been developed for typical situations: increased EI voltage, high metal level, high concentration of a key component in the melt, changes in the composition of raw materials, changes in the ambient temperature.

In Fig. 2 the algorithm of formation of the training scenario is presented.

4 Software

As a tool for creating simulator software, the SCADA system is chosen as a universal development environment that allows you to create calculation modules, dynamic visualization, and interfaces that simulate control panels at the modern level. The developed functional structure includes DB; scripts for implementing MM and training scenarios; modules for displaying information using visualization tools (animation, time graphs, dynamic display, and control elements), etc. The functional structure of the CS is shown in Fig. 3.

The software is tested on the basis of the InTouch SCADA system (based on a university license), but can also be created in other environments [16]. The software allows you to configure simulators for training in the management of objects with different sources of raw materials (when changing suppliers), different equipment, and different performance.

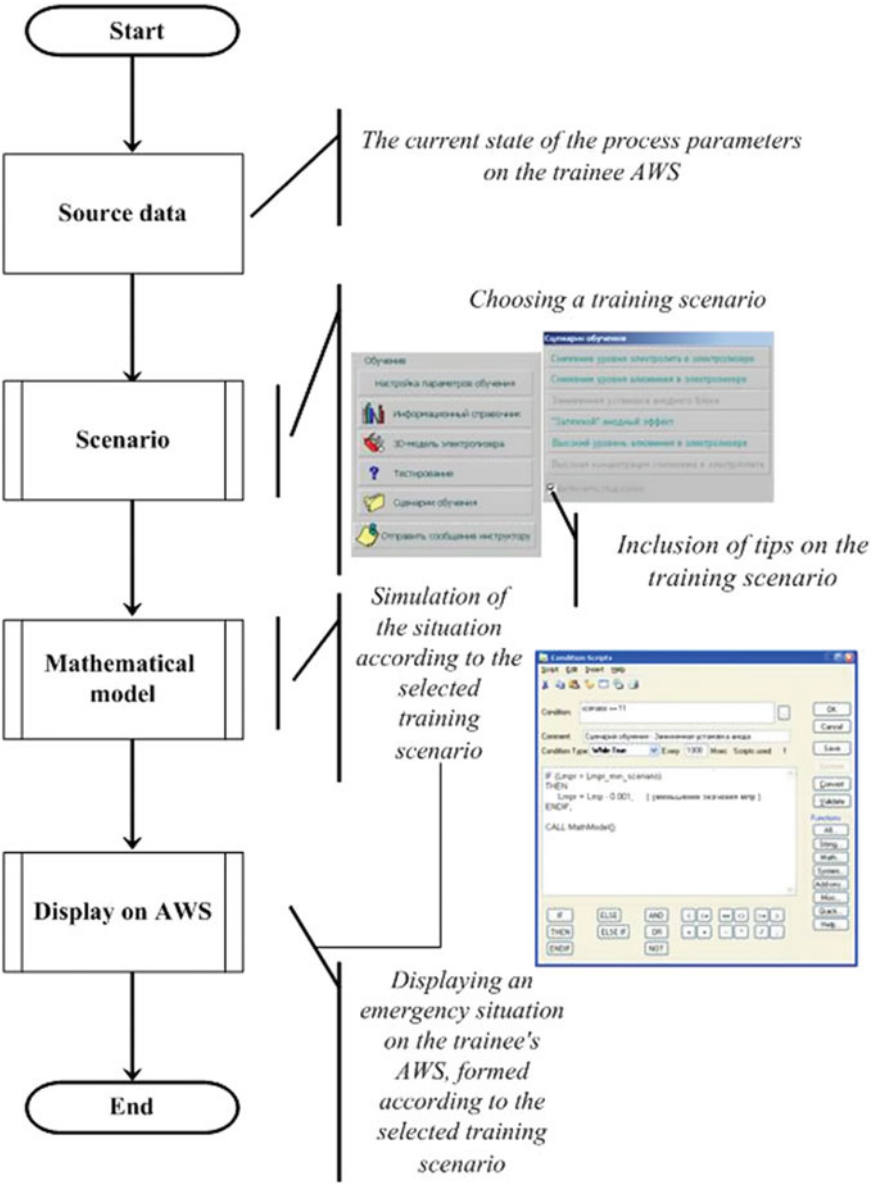

Fig. 2 Algorithm for creating a training scenario

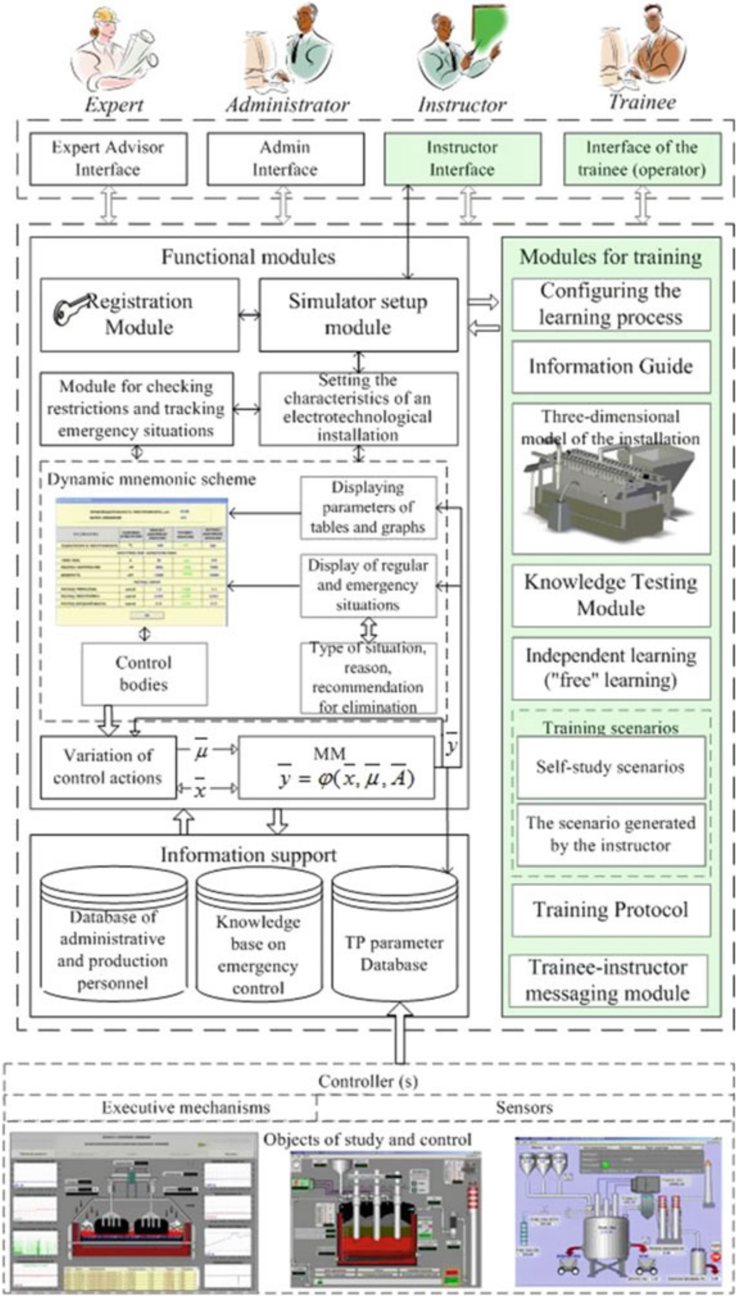

Fig. 3 Functional structure of computer simulators on the example of the production of aluminum, calcium carbide and phosphorus

Automated workstations (AWS) of trainees and instructors have been developed for training. The learner's AWS is similar to the operator's AWS and allows you to study the cause-and-effect relationships of the process, get tips on controlling emergency situations based on expert knowledge, and learn using training scenarios. The main window of the AWS operator is a dynamic mnemonic, which has a set of nested windows, controls, 3D models of equipment [21], and displays of information in the form of tables and graphs.

In the simulators, various training options are possible: studying theoretical material with the help of an information and reference subsystem; testing theoretical knowledge with the help of a testing subsystem; studying the process through a mnemonic circuit, familiarizing yourself with dynamic display and control elements, the ability to vary the values of control actions to ensure a resource-saving mode; configuring the system for specific equipment (geometry, power, performance); setting restrictions on DB parameters; study of the causal relationships of the process in the mode of independent (free) training, which results in the formation of resource-saving control skills; acquisition of behavior skills in emergency situations; work on independent training scenarios; work on the scenario set by the instructor.

AWS of the instructor is designed to organize and conduct the training process, monitor the actions of trainees, and evaluate their performance. AWS provides signaling and graphical display of information, as well as the ability to monitor and analyze the actions of several trainees from a remote computer. The instructor can initiate various training modes (individual scenarios or exam mode), intervene in the training process, and make appropriate recommendations or answer questions that arise from the trainees. Based on the results of training, a training protocol is formed, which contains the data of the trainee, the date and time of training, the scenario and the name of the simulated situations, the status of the situation (eliminated /not eliminated), the regulatory values of the parameters and their deviations from the norm. The protocol is available to the administration and the instructor and is a document for evaluating the student's qualifications.

5 Conclusion

The developed CS allows you to gain knowledge about the features of processes, study the design of equipment, conduct knowledge testing and learn how to manage processes. With their help, you can conduct initial training of operators, replenish knowledge and acquire the necessary skills of resource-saving control for operators who do not have much experience, and for experienced personnel to improve their skills. The research was carried out at the expense of a grant from the Russian Science Foundation (project No. 21-79-30029).

Methods and technologies for the synthesis of computer simulators can be used to create simulators for other classes of objects. The gym complex is a flexible configurable software package. It is based on models and algorithms for learning process control, programmatically implemented and tested in the SCADA system environment.

The method of developing simulators is tested on the example of the production of aluminum, calcium carbide, and phosphorus. Testing of simulators was carried out for Russian industrial enterprises; their performance is confirmed by the certificates of implementation in the educational process of SPbSIT (TU) and other universities, research, and production activities.

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Educational Programs' Development in the Field of Software Systems for Designing and Control Cyber-Physical Systems Using Information Modeling Technologies

Alexey Dukhanov and Tamara Chistyakova

Abstract In this chapter, we propose an approach to developing educational programs for training professionals in designing and controlling cyber-physical systems. The proposed upper-level matrix contains relations between the general needs of companies, the skills of the graduate, the relevant technologies, and the main topics of the educational program. Every relation allows us to tune the future program according to the general needs of companies, academic degrees, and domain direction. Furthermore, to structure the relevant modules/courses, we offer to use ontologies of related scientific fields and technologies. Furthermore, we proposed to apply reusable learning abstractions to fill courses with content based on existing learning resources and different forms of digital scientific results. Finally, the proposed approach is demonstrated by the example of the educational programs "Computer-aided design" designed at the Saint Petersburg State Institute of Technology and the advanced training course "Big Data and Machine Learning for Qualified Customer's Service" (ITMO University).

Keywords Educational programs · Information modeling technologies · Upper-level matrix

1 Introduction

The trends of industry 4.0 [1] determine the growth of the products and services variety, including due to the possibilities of customization with the help of modern cyber-physical systems (CPS). For example, companies can produce custom-made

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products for private clients: from unique images to specialized properties and individual forms. Such opportunities are available due to the modern capabilities of digital technologies based on classical and modern mathematical software, information, and computer modeling (for example, ontological model and artificial neural network [2]). The development and maintenance of a CPS with such capabilities are very complex and expensive processes. At the same time, errors in the design and control of such systems can lead to damage and further downtime, causing serious losses.

The software for modeling and maintenance of the CPS (including digital twins of the equipment or the digital factory in general [3]) allows reducing the given above costs significantly. The diversity of such programs is defined by the diversity of the CPS, as well as the diversity of products created and services provided. Therefore, at present, specialists-developers of such programs are in great demand.

Due to the rapid change of information technologies, the learning of such specialists should be aimed at system thinking and possession of appropriate tools (including information modeling methods), cross-cutting information technologies among them. At the same time, the relevant educational programs should be developed and continuously coordinated with representatives of companies that carry on business by means of CPS or develop appropriate software for them.

This chapter is devoted to solving the given above challenges. We will describe the development process of such programs drawing on the experience example of ITMO University and the Saint Petersburg State Institute of Technology (SPSIT). We will also consider how the proposed approach can ensure the formation of individual educational trajectories.

2 Technological Background and Related Works

2.1 What Are the Modern CPS by Nature of and Why is the Software Needed, as Well as Digital Twins?

Modern CPS are not limited to machines with digital software control. Currently, they can serve as distributed robotic technological lines capable of performing multithreaded operations on various complex templates using a wide range of raw materials and components [4]. The designing, debugging, tuning, and operation of such systems are impossible without accompanying and management software developed using cross-cutting technologies [5]. It is very important to tend to zero probability of failure by maintenance such systems [6] since the cost of their downtime and repair is very high. An example of such a system is intelligent heavy sawing machines [7], an automated line for the recovery of aluminum and lithium-iron-phosphate components from spent lithium-iron-phosphate batteries [8], and extrusion and calendrer lines for film materials production [9], (Fig. 1).

Fig. 1 Extrusion and calendrer lines for film materials production

Therefore, in the different industrial branches, CPS is a very expensive programable complex distributed system, which can perform different operations depending on the specified scenario. Maintenance and operation of these devices require high qualified professionals with skills in system analysis, mathematical modeling and computer simulation, control theory, and software application design and implementation. In this chapter, we offer the top matrix, which represents scientific means and technologies, general internal corporate needs, skills, and learning topics for the educational program to learn high qualified professionals in the area of design and control of CPS.

2.2 Cross-Cutting Information Technologies

In this chapter, we do not touch in detail on cross-cutting technologies. But they are directly related to the design and control of cyber-physical systems. Therefore, we will give brief information about them.

In the last couple of decades, Machine Learning technologies have been the means of automatically detecting patterns in arrays of different types of data and are widely used, including in classification and forecasting tasks [10]. BigData technologies are shifting modern research and related engineering solutions in favor of data-centric architecture and operational models [11]. Virtual and augmented reality technologies (in some works, for example [12], such technologies are called Extended Reality) not only allow to present data and models of objects in a convenient form for a person[13] but also are a powerful tool for conversational interaction with the CPS. Due to the high cost of the CPS, AR/VR technologies in the period of Industry 4.0 are almost always used in the development of appropriate learning tools, including simulators [14]. Also among the cross-cutting technologies are distributed registry ones and the Internet of Things, without which it is difficult to imagine modern CPS in the trends of Industry 4.0 [15]. In recent years, quantum technologies have been actively used for the design of intelligent CPS [16].

2.3 Overview of Approaches that Facilitate the Development of Educational Programs

In the educational direction, there is a large number of scientific works related to all stages of the development of educational programs: the formation of general requirements taking into account the opinions of companies' representatives, structuring, and content development. The negotiation approach is presented in the work [17]. This approach makes the course being developed more relevant to the requirements of all interested participants in the educational process. By developing, it is very important to organize processes scaffolding in the development and implementation of educational programs. The paper [18] shows the application of this approach in order to reduce the costs of teachers for formal and technical actions when developing a course.

A smart card method is a powerful tool in the development of concepts and the design of various systems. IMA-CID ontology is used for structuring and developing course elements [19]. In the paper [20], the authors showed an increase in the number of ideas that students formulate using this method. The authors of the work [21]showed using a mindmap to form the means for runtime verification taxonomy. The smart maps approach is also used to represent technology taxonomies. In particular, the GitHub resource[1] presents a set of intelligent maps of scientific methods, technologies, and tools related to Machine Learning.

Consequently, this approach allows us to perform automatic generation of electronic educational content suitable for multiple platforms, including mobile devices [22]. The formation of educational content using the concept of abstract hybrid learning resources [23] allows us to cover numerous interdisciplinary issues appropriate to many different learning outcomes.

3 Development of an Educational Program

3.1 Creating the Top Matrix for the Development of an Educational Program

To develop an educational program, we primarily rely on modern scientific and technological directions, as well as the general needs of companies that use or develop CPS. These directions and needs are determined based on the study of arrays of scientific articles and other sources related to the considered field. It is also very important to attract representatives of relevant companies. In general, we held a number of meetings with representatives of international industrial companies for

[1] https://github.com/dformoso/machine-learning-mindmap?utm_content=bufferccd3b&utm_medium=social&utm_source=twitter.com&utm_campaign=buffer.

the production of polymer films Klöcker Pentaplast Europe GmbH & Co, Kohlert-Consulting (Germany), the factory in St. Petersburg JSC (Joint Stock Company) "Plastic Processing plant named after Komsomolskaya Pravda" (Russia), as well as petrochemical and oil refining enterprises: PJSC Gazprom Neft, PJSC NK Rosneft (Russia). By forming a list of companies' needs, a list of scientific and technological areas that these needs can cover was directly determined. By forming the list of scientific and technological directions, we took into account not only the needs of companies but also the trends in the development of cross-cutting technologies, as well as technologies used in the design and maintenance of the CPS. The needs themselves are formulated in terms of technological processes, not competencies. Also, the formulation of competencies is carried out taking into account educational standards and other regulatory documents. Therefore, the competencies (skills) are formulated separately but are brought into accordance with the representatives of the companies.

Below is a list of needs, as well as scientific and technological directions.

The needs of companies:

- Structural Design of the CPS (CPS_SD);
- Modeling and Forecasting of the CPS Activity and their Components (CPS_SF);
- Decision-Making Support in the Organization and Control of the CPS (CPS_DS).

Scientific and technological directions:

- Machine Learning and Cognitive Information Technologies (ML&CIT) [24];
- Methods for modeling CPS and Related Processes (CPSS);
- Optimization and Optimal Control Methods (OM&OC);
- Technologies of Algorithmization, Software Design and Implementation (ADDS) [25];
- Systems of Statutory Documents in the Design, Implementation, and Application of Software (SST).

The links indicate the sources in which the authors' experience in the application of appropriate technologies in the design and control of the CPS is presented.

The scientific means and technologies of the above-presented directions may overlap. But this effect is an advantage since it determines the possibility of repeating the material in passing to the development of new directions and levels of competencies.

Note that the list of technological solutions does not include cross-cutting technologies "Internet of Things" and "Distributed registry Technologies". They are a powerful basis for the development of distributed CPS, but now the companies with whose representatives the meetings were held have been notified that they prefer more desktop versions of software or network systems that work using standard protocols. This decision is not caused by the low competence of the company's representatives. The companies should have changed, but they should be carried out at a reasonable pace and by means of technologies that have been repeatedly tested in real life.

After the general needs of companies and scientific and technological directions are formulated, we can proceed to the formulation of the graduate's competencies. Competencies are formulated by verbal turns and the abilities are determined that a person should possess after the successful completion of the program. They should invoke the above-presented directions and show the possibility of covering the needs of each company's employee who successfully completed the educational program. Soft Skills and general professional skills are the same for all software programs. Therefore, in the list below, we present only professional skills:

- to analyze production requirements, technological processes of creating a given product, state the formulation of algorithmization and programming tasks (PS1);
- to develop mathematical and computer models, solve optimization problems for maintenance and decision-making support in production control by means of CPS (PS2);
- to carry out the conceptual, functional, and logical design of software packages for CPS maintenance (PS3);
- to implement software packages for CPS maintenance (PS4);
- to prepare documentation for software packages under development (PS5).

Having received the above lists, we can proceed to the educational topics' formulation of the educational program's professional module. Each topic corresponds to one or more disciplines. But at this stage, the topics do not determine the curriculum. They show educational events at the conceptual level. Such events provide students with the necessary skills by teaching appropriate scientific and technological tools from the areas given above. The list of topics should not repeat the list of scientific and technological directions. It should ensure the conciliation of the educational process, taking into account earlier learning events in the educational program for soft–and general professional skills provision,[2] as well as the educational process built in the relevant department. These events are reflected in the educational programs of bachelor's degree preparation, for example, "Computer-Aided Design System" [26].

The formulation of topics using the above-mentioned lists and taking into account the above-mentioned requirements is difficult. Therefore, it is proposed to write out these lists in the form of a two-dimensional structure so that you can see the potential connections between their elements: covering the general needs of companies with technologies and skills, covering technologies and skills with educational topics. Here we used the matrix approach and took the X-Matrix as a basis.[3] However, its content becomes different. We called such a matrix "Upper-Level" because it gives general ideas about the educational program both for participants in the educational process and for employers. The template of such a matrix is shown in Fig. 2.

In the upper part (the northern part of the matrix), the general needs of companies (Intracorporative Needs) are recorded. It is recommended to write them down from the bottom up, taking into account the product's life cycle stages, the sequence of

[2] Such activities include the development of approaches to studying the object and subject of research (including a literary review), system analysis, algorithmization and general programming.

[3] https://kanbanize.com/lean-management/hoshin-kanri/what-is-hoshin-kanri-x-matrix.

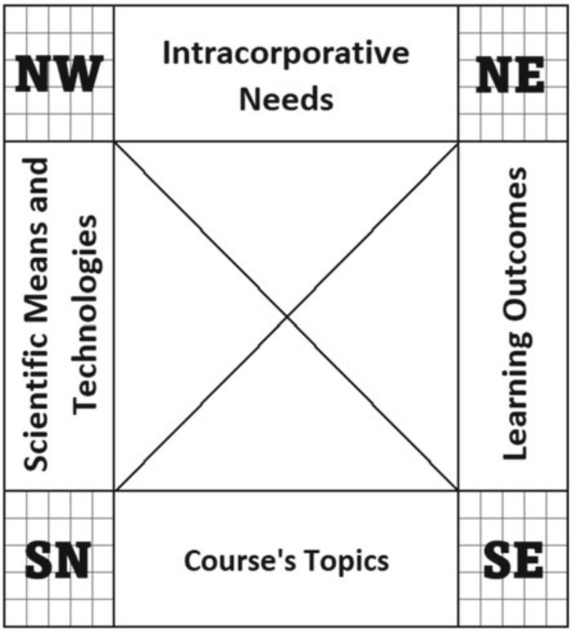

Fig. 2 Template of the upper-level matrix for educational programs' development

its stages, or the complexity level of solving needs. On the left (the western part), the scientific and technological directions are written. We recommend entering them from right to left based on the above-mentioned logic. Competencies are added to the eastern part of the matrix. They are entered from left to right in accordance with the order of their provision. The southern part of the matrix is filled with educational topics from top to bottom in the order of relevant activities' implementation.

There are filled tables at the vertices of the matrix diagonals, that reflect the relationships between needs, scientific and technological directions, skills, and educational topics. If there is a corresponding relationship, then it is reflected in the form of "X" characters: from one to three ones. The values of the relevant symbols for each matrix vertex (NW, NE, SE, and SW) are shown in Table 1.

3.2 *The Upper-Level Matrix for the Educational Programs' Development in the Field of the Software Packages' Development for the CPS Maintenance*

In Fig. 3 the completed upper-level matrix for the educational programs' development in the field of the software packages' development for the CPS maintenance is presented. This matrix represents the possibilities of implementing the relevant educational program in the maximum version. It is interesting not only for the general coordination of the directions and content of educational cooperation between the

Table 1 Indications of relationships between the main elements of the matrix

The number "X"	The relationship between:			
	Needs and means determined by the directions (NW)	Needs and skills (NE): application of competencies at the level of:	Skills and topics (SE): development of competence to the level of:	Topics and directions (SW), the mastering of appropriate means at the level of:
1	Application as an auxiliary tool	Descriptions and examinations	Understanding	Overview
2	Application as a fixed tool with its alternative replacing possibility	solutions to clearly defined tasks	Applications	Applications
3	Application as a critical tool	Solving the problems of creating something new	Critical analysis and development	Development

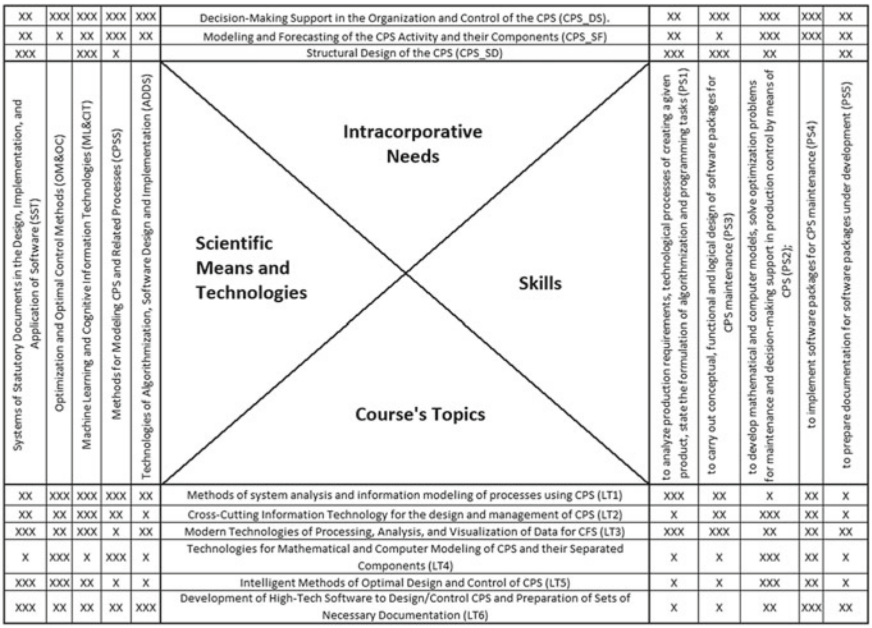

Fig. 3 The upper-level matrix for the educational programs' development in the field of the software packages' development for the CPS maintenance

participants of the educational process (scientific and pedagogical workers and the university administration) and interested companies but also for their development in the directions indicated in the western part.

At the same time, this matrix can be quickly adjusted in case of changes not only in technologies but also after high-level decisions affecting the activities of the collaboration participants.

To develop an educational program for a specific level of education, the resulting matrix needs to be clarified. First of all, the clarifications relate to the relationships' levels. In particular, for the bachelors' preparation, it is sufficient to ensure the development of competencies at the level of understanding and (or) application. For the master's degree, the level of competence can be increased.

3.3 Features of the Upper-Level Matrix Application for the Development of Further Vocational Education Programs

Of particular note is the development of programs for short-term further vocational training. For such courses, the matrix will remain unchanged if the competencies are mastered at the level of understanding. In other words, further vocational training becomes an overview for a superficial update of knowledge (Refresher Course). A similar course, called "BigData and Machine Learning for Qualified Customer's Service" was developed for top managers, middle managers, and other technology leaders.[4]

If it is necessary to develop a course for the practical development of scientific methods and (or) technologies (Advanced Training Courses), the matrix should be adjusted by eliminating unnecessary entities. Thus, for the course "Intelligent Optimization Methods for Computer Modeling", developed at ITMO University at the request of PJSC Gazprom Neft: Scientific and Technical Center, only the entities LT4, OM&OC, CPS_DS, and PS2 were left in the matrix. The latter was narrowed down to "The ability to apply basic and intelligent optimization methods to solve problems of increasing the efficiency of individual teams and divisions in solving production tasks".

Thus, by means of the matrix, it is possible to form a large number of both individual further vocational training programs and individual educational trajectories. In such a situation, it is very difficult to cover all the options of trajectories in a natural way. Therefore, it is necessary to solve the corresponding automation problem. The solution to this problem, which is a separate study, is possible by creating a production model of knowledge.

The adaptation of the matrix (Fig. 3) for bachelor's and master's degree programs at SPSIT is given in Part 4 of this chapter.

[4] https://news.itmo.ru/en/education/trend/news/10303/.

3.4 Formation of the Program Content

To get to the program content, it is necessary to decompose the specified scientific and technological directions into sections and appropriate tools (methods, techniques, technologies, algorithms, etc.). For doing this it is possible to use both ready-made direction structures and smart maps of the corresponding technology groups, or develop one's own taxonomies/smart maps. The list of disciplines is formed on the basis of the obtained upper-level matrix, as well as the above-mentioned maps.

Smart maps of BigData and Machine Learning technologies can be quickly found both in scientific sources, in blogs and posts, and in public web services for collaborative work.[5] It was not possible to find generally accepted taxonomies of BigData and Machine Learning as cross-cutting technologies. This is due to the fact that these areas are actively developing and the lifetime of a particular digital technology does not exceed two years. Therefore, it is better for developers of an educational program together with representatives of companies to determine the appropriate smart cards independently.

For a structural description of the program's content and the relevant disciplines, we propose to use frame modeling that has been modernized for the design of training courses and educational trajectories [23, 27]. This simulation allows the building of so-called basic learning resources (BLR) [23]. Using the logic of frame modeling, Individual Learning Resources (ILR) are created on the basis of basic learning resources. They are based not on elements of taxonomies and (or) intelligent direction maps, but on information resources and reusable learning objects (RLO). Information resources are ready-made scientific and technical solutions (scientific and technical products [28]) presented in the form of information objects of the following forms: scientific article, software documentation, high-tech software solution. The use of such resources makes it possible to teach students using examples related to specific cyber-physical systems. In other words, the student has the opportunity to master high-tech technologies using real examples. To master the basics of the corresponding element of the intellectual map (taxonomy), existing RLOs are used [23]. Such objects are effective when it is difficult for a student (especially at the bachelor's level) to delve into real problems. Therefore, they may be offered simpler learning tasks. Due to this approach, the development of a content is transformed into the assembly of educational materials based on existing resources, taking into account the personal parameters of individual courses and individual characteristics of students.

We will show the advantages of using BLR and ILR. In Fig. 4, it is presented without using these structures. The section "Genetic algorithms" from the taxonomy of optimization tools is associated with two entities: a reusable educational object

[5] https://github.com/dformoso/machine-learning-mindmap?utm_content=bufferccd3b&utm_medium=social&utm_source=twitter.com&utm_campaign=buffer; https://www.mindmeister.com/ru/547743421/bigdata.

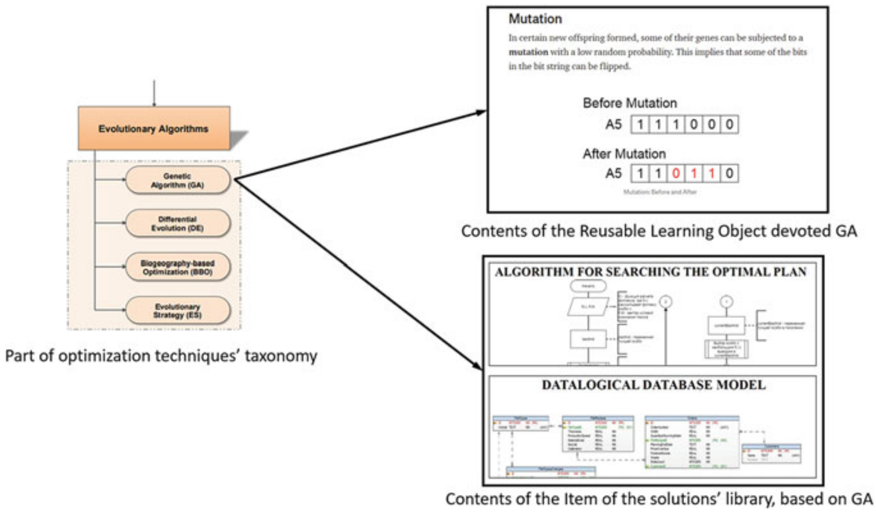

Fig. 4 An example of relationships between an element of an intellectual map (taxonomy), information resources, and educational objects

describing genetic algorithms with educational examples,[6] information object reflecting a scientific and technical solution: a software package for optimal planning of the production of polymer materials using a genetic algorithm [29].

Presented in Fig. 4 the scheme reflects only the subject and resource side of the educational process. To take into account the educational side, including the level of education and types of learning activities, we use abstract hybrid learning resources or basic learning resources (BLR) [23]. In such a structure, you can not only refer to information objects and reusable educational objects but also set educational subject, and technical parameters. In addition, such structures provide for the main types of learning activities, which could be varied depending on the level of education, the subject orientation of the course, the current purpose of learning, and other educational tasks. The variation is determined by methods that can have the same name but are described in different ways (the principle of polymorphism in the object-oriented approach).

Figure 3. shows an example of a BLR for training on the use of genetic algorithms for solving CPS control problems. This BLR refers to three information resources (IR) and two RLO. IR and RLO are the content on the basis of which students will be learned. The rules/recommendations for using this content are contained in the methods that are used depending on the values of the BLR parameters. Figure 5 shows the possibility of using the BLR "Genetic Algorithms for CPS" in terms of a preliminary study of materials and performing laboratory works, depending on the

[6] https://towardsdatascience.com/introduction-to-genetic-algorithms-including-example-code-e396e98d8bf3.

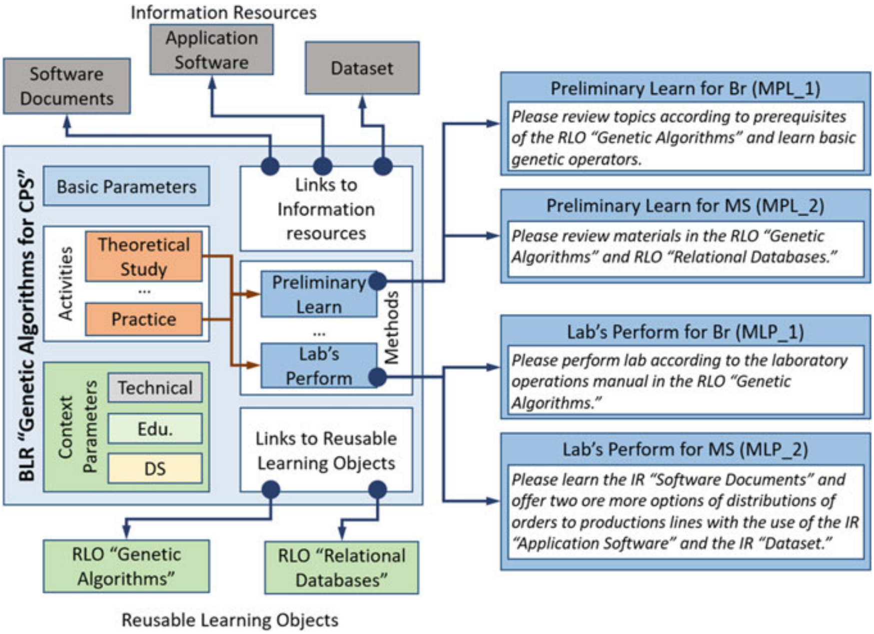

Fig. 5 An example of a BLR based on a software tool, data, and documentation to support decision-making in the control of a technological film cutting line

level of education: bachelor's degree (Br) and Master's degree (MS). The preliminary study of materials (as a form of the "Theoretical Study" event) for the undergraduate level is based on the prerequisite part of the RLO "Genetic Algorithms" (MPL_1 method). For the master's level, it is proposed to recall the main theoretical materials from the same RLO, as well as the RLO "Relational Database" (MPL_2 method). It is proposed to take information and data for performing laboratory work for the bachelor's level from RLO "Genetic Algorithms "(MLP_1 method), and for the master's level from IR: "Software Documents ","Application Software ", and" Dataset" (MLP_2 method). Alternatively, you can use an article describing the solution in planning the movement of urban passenger transport using a genetic algorithm [30]. Some of its parts can be used as teaching material for undergraduate students. This material shows the application of the genetic algorithm in a real complex system.

Thus, the presented BLR for undergraduate students can be used for the initial study of the genetic algorithm, as well as for the practical application of this algorithm for real data. At the same time, the same BLR can be used to develop options for the distribution of film cutting tasks on the production line as a CPS for making production decisions.

Automation of the selection of methods depending on the parameters can be implemented using polymorphism, as shown in [23], or by creating and using a system of production rules. For example, the rule:

```
IF (Degree = "Masters" and Domain = "PMP" and LearningTech =
"Flipped Learning" THEN {
- Activity["Theoretical Study"] is "Preliminary Learn" = MPL_2;
- Activity["Theoretical Study"] is "Lab's Perform" = MLP_2
}
```

shows that in the case of using the "Inverted Class" educational technology for master's students who are studying in the field of polymer materials production, it is necessary to: define theoretical study as a preliminary study of materials using the MPL_2 method, and conduct a practicum in the form of performing laboratory work using the MPL_2 method. The development of a method for the formation of such production rules and the corresponding domain-specific language is a separate study planned by the authors on the basis of [27].

4 Formation of Programs for the Bachelors' and Masters' Learning

In the previous part, we showed the formation of the top matrix and concepts of the content building based on technologies mind maps, and reusable learning abstractions (BLR). We have presented how the same resource can be used for different levels of education. Now we will show the adaptation of the upper-level matrix for the following degrees: masters and bachelors. Adaptation is based on the fact that the lower the degree, the fewer requirements for the development of competencies and work with scientific tools and technologies. Thus, at first, we will receive a matrix for the master's program. Later we will receive a matrix for the program of bachelor's degree.

A professional with a master's degree is required to possess most of the skills at the application level (XX). He must have the key skills at the level of critical analysis and modernization of the relevant tools. But unlike the Ph. D., the master's degree is more for practical professionals. Therefore, the corresponding relationships between the elements of the matrix are adjusted in the direction of reducing the number of characters "X" (Fig. 6 a).

For example, the master is required to select and apply methods of system analysis and information modeling for the formulation of CPS design tasks. But he does not need to conduct a critical analysis of the relevant methods/methodologies in order to modernize the established procedures. Therefore, in the south-eastern part of the matrix, the number of "X" characters was reduced to two at the intersection of the educational topics LT1 and PS1.

A specialist with a bachelor's degree has lower requirements. In most cases, he does not need to make changes to scientific tools and technologies. For example, a bachelor must master cross-cutting information technologies in order to apply Machine Learning and "KIT" for the design of CPS (Fig. 6b). But he does not need to develop a unique Machine Learning model or perform a modification of the selected

XX	XXX	XXX	XXX	XXX	CPS_DS	XX	XX	XXX	XX	XX
XX	X	XX	XXX	XX	CPS_SF	XX	X	XX	XX	XX
XXX		XXX	X		PS_SD	XX	XXX	XX		XX
SST	OM&OC	ML&CIT	CPSS	ADDS	ICN / SM&T / Skills / CT	PS1	PS3	PS2	PS4	PS5
XX	XX	XXX	XX	XX	LT1	XX	XX	X	XX	X
XX	XX	XXX	XX	X	LT2	X	XX	XXX	XX	X
XXX	XX	XX	X	XX	LT3	XX	XX	XX	XX	XX
X	XX	X	XX	X	LT4	X	X	XX	XX	X
XX	XXX	XXX	X	X	LT5	X	X	XXX	XX	X
XX	XX	XX	XX	XXX	LT6	X	X	XX	XXX	XX

(a)

XX	XXX	XXX	XXX	XXX	CPS_DS	X	XX	X	XX	X
XX	X	XX	XXX	XX	CPS_SF	XX		XX	XX	XX
XXX		XXX	X		PS_SD	XX	XX	X		XX
SST	OM&OC	ML&CIT	CPSS	ADDS	ICN / SM&T / Skills / CT	PS1	PS3	PS2	PS4	PS5
X	X	X	X	X	LT1	XX	XX	X	XX	
X	X	XX	XX	X	LT2	X	X	XX	XX	X
XX	X	XX	X	XX	LT3	X	XX	XX	XX	X
X	X	X	XX	X	LT4		X	XX	XX	
X	XX	XX	X	X	LT5	X	X	XX	XX	X
XX	XX	XX	XX	XX	LT6	X	X	X	XX	XX

(b)

Fig. 6 Upper-level matrices adjusted for **a** master's degree program; **b** bachelor's degree program

KIT. Therefore, at the intersection of LT2 and ML&CIT scientific and technological directions' educational topics, the number of "X" characters is one less than in the master's matrix. In some cases, within the framework of a given educational topic, it is enough for him to master the skill at the level of understanding. For example, for the design of a CPS, it is enough only to understand the methods of mathematical and computer modeling. Therefore, there is only one "X" symbol at the intersection of the LT4 educational topic and the PS3 skill.

For the level of education corresponding to the Bachelor's or Master's degree, each academic topic can be assigned according to one or more courses. In the case of several courses, the matrix can be refined.

5 Conclusion

In this chapter, we proposed an approach to the development of educational programs for training professionals in the field of design and control of cyber-physical systems.

The approach is based on the deductive principle. First, four lists are formed: (1) the needs of companies that expect graduates of programs; (2) a list of scientific and technological areas that allow the needs to be covered; (3) a list of skills that graduates must possess in order to meet the needs of companies; (4) a list of educational subjects on which the program is implemented. Such elements are interconnected. Relationships reflect how some elements cover others, for example, with educational topics-competencies or scientific and technological solutions-competencies. To display lists and relationships on the same plane, an upper-level matrix is proposed. It allows to development and coordination of the main outlines of the future educational program in a short time with the involvement of companies' representatives, as well as external experts. The obtained upper-level matrix is specified for the bachelor's and master's levels.

In order to structure and fill the program with content, it is proposed to choose or set the ontologies of the selected scientific and technological directions and to collect and configure the so-called basic learning resources (BLR) for their terminal nodes. Their assembly is based on information resources (software, documentation, scientific articles) and reusable educational objects. When updating the specified resources and objects, the necessary educational content is automatically updated. BTR can be adapted both to the levels of education or skills, and to specific subject areas by setting the values of various types of parameters, choosing educational technologies, and determining how to use educational content.

Thus, the methods and technologies of information modeling are proposed, which allow forming educational modules and levels of their development on the basis of a matrix flexibly adjusted to the challenges of industrial enterprises, as well as innovative information technologies.

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A Vector Representation of the IT Specialists' Set of Workloads for HR Decision Support System

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Abstract The chapter addresses the model of forming a set of IT specialist workloads reflecting employers' demands based on vacancies texts set. An approach to the workload analysis as a set of specialists' competencies (skills) is proposed. A method for the periodic data collection of IT specialist vacancies localized by region is defined. The method of skills extraction from vacancies texts via textual data normalization and named entities extraction is described. Different approaches to the vector representation of skills and vacancies texts are examined, including one-hot encoding, word2vec, latent Dirichlet allocation, encoding using smooth TF-IDF metric. Cluster analysis has been chosen as the primary method of identifying interrelated competencies groups and forming a set of workloads. The authors compare a number of approaches to the identification of interrelated competencies groups and propose the principle of fuzzy clustering of skills. The quality of the groups obtained this way is evaluated by two methods: an automated evaluation score based on the similarity of vacancies titles in one group is calculated, and an expert assessment from IT specialists and teachers is received. The evaluation results for the proposed clustering method aimed at the workload set forming for the Russian regions are compared with each other. The chapter also describes the application of the developed model in the decision support system to improve personnel management in the industry through targeted training and retraining of applicants.

Keywords IT specialist · Skill · Competence · Cluster analysis · Quality evaluation · Vectorization · Workloads

1 Introduction

The problem of discrepancy between the skills of applicants and the employers' demands is relevant for the contemporary labor market. The main challenges for the requirements formulation arise in actively developing industries, in which skills

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are dynamic in nature. One such field is IT. The number of vacancies published during 2018 in major cities exceeds 135 thousand [1]. At the same time, educational institutions annually produce 43 thousand specialists in the field. According to the statistics, 56.4 thousand students were admitted in the academic domain "Informatics and Computer Science" for bachelor's, specialist's, and master's degree programs in 2018 [2]. The demand for IT specialists is evident in all developed countries, with the personnel shortage being quite acute [3–5]. The problem of discrepancy between employers' requirements and specialists' competencies is particularly relevant in this industry.

The present work is based on various studies on the problem of training highly demanded specialists. In the works of Yusoff, Omar et al. [6], De Castro et al. [7], Podvesovsky et al. [8], Smith and Ali [9], Ilyin et al. [10] the process of skills extraction from vacancies reflecting the employers' demands are reviewed. Podvesovsky et al. [8] proposed CLOPE cluster analysis algorithm to aggregate similar skills, but the selection of skills was done manually. Smith and Ali [9], Ilyin et al. [10] suggested an automated collection of data from vacancies aggregator sites. In the first paper, the daily monitoring of specific skills from the Dice.com is described, and in the second one, HH.ru and Indeed.com are considered as the data sources. The work of Ilyin et al. [10] describes an information system that allows the selection of the most relevant skills for further studying.

The present study aims to develop an integrated model to increase the employment probability and allow applicants to compile a list of skills that employers expect from a professional. The prototype application automates the collection of employers' demands. It is proposed to vacancies' descriptions used as a data source and identifies the skills that, according to the employer, a specialist in the field should possess. Based on the collected data, it is suggested to form a workloads set. Each workload defines a group of skills for one programming field. This chapter explores the application of several textual data vectorization methods and proposes a quality evaluation of clustering, based on the vacancies' titles.

2 Data Collection and Processing

The job aggregator site HH.ru was chosen as the source of vacancies texts. The site allows interacting with the published vacancies data via its API [11]. The restriction of the IT domain was implemented by using the "Programmer" query keyword. It was also localized by region. The data was exported once a month. For this study, the following data were extracted from the vacancies: keywords metadata, region, vacancy description, vacancy name, unique vacancy identifier.

A list of unique skills that appear in the IT domain was generated from the keywords metadata. Metadata normalization was performed to identify unique skills and a dictionary was formed consisting of skill in normal form and skill from the metadata. The normalization includes a number of steps: tokenization, converting words to lower case, clearing punctuation using regular expressions, clearing stop words, and using the pymorphy2 morphological analyzer [12] to extract the normal form of the word.

Then, a similar normalization algorithm was applied to the vacancies' descriptions. Skills were retrieved using the n-gram method [13] by comparing the normal form of skill from the metadata and n-gram sequences from normalized vacancies descriptions. Thus, complex skills consisting of several words, such as "Micro Controller Unit", were identified, among others.

Since semi-structured natural language data are processed, in order to structure the data and identify the groups it is necessary to convert it into a vector form, taking into account the domain specifics.

3 Vectorization

The goal is to identify competencies that characterize an aspect of programming or a role in a company. Employers are looking for employees to solve certain task sets. The collection of these groups can be considered as a sought set of workloads. Thus, the problem can be reduced to the clustering task—a division of the set of examined objects and attributes into groups homogeneous in some way. Since the clustering algorithm receives vectors as an input, it is necessary to develop a technique of vector representation of competencies contained within the texts of vacancies [14].

As a part of the study, a number of vectorization techniques applied to both competencies and vacancies' texts were explored. The first method examined is unitary encoding, which consists in converting a word into a binary vector. In the context of our work, a skill is vectorized, the presence or absence of skill in each individual vacancy (1—if the skill is present in the vacancy, 0—if the skill is absent) forms a set of features.

We used the affinity propagation clustering algorithm, which automatically determines the number of clusters depending on the data set. The algorithm assumes message exchange between all data points. Each point sends messages to all other points with information about the relative "attractiveness" of each "leader" point. Each leader then sends a message to the points about its availability to communicate with the sender, taking into account the attractiveness of the messages received from all the other senders. The coefficients then recalculate the attractiveness taking into account the availability it received from the leader. Messages are sent until the coefficients are adjusted. As soon as a point is associated with a leader, the leader becomes the reference point. All points with the same leader are placed within the same cluster [15].

The silhouette coefficient was used to evaluate the quality of clustering [16]. The silhouette coefficient is calculated by the following formula:

$$s = (b - a)/max(a, b)$$

where a is the mean distance between elements within a cluster; b is the mean distance to the nearest cluster.

The best coefficient value is 1, the worst value is –1. Values close to 0 indicate overlapping clusters. Negative values indicate that the sample was assigned to the wrong cluster and there is another, more appropriate cluster.

The standard metric "silhouette_score" provided by the Scikit-learn library was used for the software implementation of the coefficient calculation. The clustering results for different periods and different regions were analyzed. It was found that the median silhouette coefficient for a binary vector is 0.23; it led us to seek ways of improving the vectorization technique in order to raise the clusters' quality.

Investigating natural language processing methods, we considered an algorithm that takes a bag of words as its basis [17]. Using this method, the frequency of word usage is counted, and the frequency of skill lexemes in the vacancies texts is written into the vector.

To evaluate the efficiency of the modified vectorization algorithm, the silhouette coefficients for a number of regions and periods were compared. The results of some estimates are presented in Table 1.

The coefficient comparison reveals improved clustering results.

The technique successfully identified groups of competencies corresponding to the target domain (an example set is shown in Fig. 1), but the hard clustering, where

Table 1 The silhouette coefficient

Region	Monitoring date	Silhouette coefficient. Binary vectorization	Silhouette coefficient. Lexical frequency
Perm Krai	20–08-05	0.297	0.422
Perm Krai	20–04-05	0.301	0.420
Krasnodar Krai	20–04-05	0.351	0.494

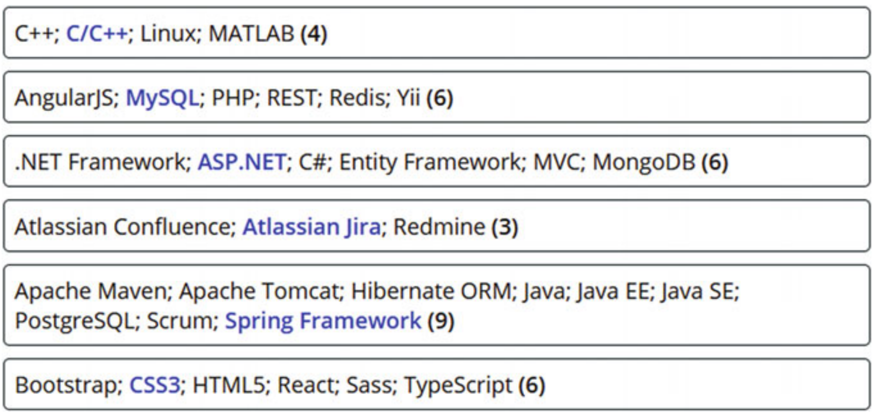

Fig. 1 A fragment of the competencies' groups set, Perm Krai, August 2020

each skill is placed strictly in one group, does not reflect the fuzzy nature of the competencies set.

For instance, the version control system "git" may be present in several subsets of workloads, but with the described vectorization and clustering method, "git" appears in only one subset. The given estimations confirm it, because the silhouette coefficient lies between 0.4 and 0.5. It indicates a strong overlap of clusters.

To remove this limitation, the word2vec method was tested. The method is based on neural networks. First, a dictionary is created, which needs to be trained. Then a vector representation of words based on contextual proximity is computed. Close words in the corpus of texts retain the closeness of the coordinates in the vector representation [18]. Despite the fact that the constraints associated with hard clustering in word2vec do not occur, the effectiveness of this method to solve our problem is not sufficient. The nearest contexts for skills are often words that are not specific to the domain, such as "team", "confidence", etc. Also, the inability to control which features the algorithm allocates to a particular skill makes its use for the task unacceptable, since the skill is not always equal to its linguistic context in the vacancy text.

Since the competencies related to the same workload are likely to occur in the vacancies' texts for similar positions, the solution to the issue of reflecting the fuzziness of the competencies set can be in the grouping of the actual vacancies' texts. To implement this approach, we considered the method of topic modeling by Latent Dirichlet Allocation (LDA) and non-negative matrix factorization (NMF). This method involves considering the documents as a set of topics and the topic as a set of words. This decomposition makes it possible to associate documents with topics in natural languages and to form groups not based on discrete division [19].

The best results are shown in Figs. 2, 3, 4 for the St. Petersburg region in April 2021.

The topic in Fig. 2 covers Java programming language technologies and includes the platforms and frameworks that are used in Java programming. The topic in Fig. 3 combines programming languages, document markup language, and frameworks that web programmers use. However, not all the topics are formed correctly. For example, the topic in Fig. 4 contains words frequently used in the position descriptions, but these words are of common nature, are not skills, and are non-informative in terms

Fig. 2 "Java" topic. St. Petersburg, April 2021

Fig. 3 "Web Development" topic. St. Petersburg, April 2021

Fig. 4 "Motivational" topic. St. Petersburg, April 2021

of topic formation in the context of the domain. Despite the qualitative formation of some topics, this method is not suitable for building a group of specialists' skills, because the vacancies descriptions include not only skills but also template phrasings, which are not intended to be filtered by this method.

Another disadvantage of this method in the context of our work is the necessity to define the number of topics. Since different regions have different numbers of vacancies, and some vacancies' texts are rather short, it is required to run multiple models and compare their metrics in order to determine the optimal number of topics, which significantly slows down the processing in the case of dynamically received data.

The reviewed methods, their identified advantages, and disadvantages showed the need for a specialized method for a given domain.

4 A New Approach to Workloads Set Forming

To eliminate the disadvantage of hard clustering, a different approach to cluster formation was proposed. Vacancies texts were taken as clustering objects. Each vacancy description was normalized and vectorized using a smooth TF-IDF algorithm, where TF is "term frequency" and IDF is "inverse document frequency", with the following formula:

$$TfIdf = \left(\frac{f_i}{k}\right) * log\left(\left(\frac{1+n}{1+df}\right) + 1\right)$$

where f_i is the number of occurrences of term i in the vacancy, k is the number of terms in the vacancy, d is the number of vacancies in the region, df is the number of vacancies in the region where term i is used.

TF-IDF is a statistical measure used to evaluate the importance of a word within the context of a document that is part of a document collection or corpus. The weight of a word is proportional to the frequency of the word usage in the document and inversely proportional to the frequency of the word usage in all the documents of the collection [20]. To create a vector space that takes into account the specifics of the domain only lexemes that are part of skills are used as features. The method of obtaining the bag of words from which these lexemes were derived is described in Sect. 3.

Then, the vectorized data were clustered. The final clusters included vacancies identifiers. The next step was skills extraction. For each vacancy identifier, a respective vacancy description was analyzed, and skills were extracted using the n-gram method, as described earlier. This approach allows us to remove the limitation of hard clustering consisting in attributing a skill only to one cluster. As a result of this clustering skills that can be part of different programming fields (as in the "git" example given previously) appear in several clusters. These results better represent the labor market situation.

To rank skills within groups, each skill was assigned a weight coefficient that determines the importance of the skill for a given subset of workloads. The weighting factor was computed as the sum of the Boolean occurrences of the skill in the vacancies descriptions in the cluster divided by the number of vacancies in the cluster. Skills in clusters are sorted in descending order by weight and restricted to a weight value greater than 0.2. An example of clustering using this method is shown in Fig. 5.

It is to be noted that the silhouette coefficient for this approach is not informative, as the resulting groups are not the immediate clustering output. Therefore, this metric was not applied.

5 Clustering Quality Evaluation

Due to the inability to use the silhouette coefficient as a clustering quality evaluation measure, an evaluation technique based on vacancies titles was developed, since often the vacancy title determines the vacancy's place within the domain. The outcome of this evaluation is the coefficient calculated by the formula:

$$s = max(pn)/a$$

Java (1); Spring (0.88571); Git (0.6); PostgreSQL (0.57143); Maven (0.54286); SQL (0.45714); ORACLE (0.45714); Spring Boot (0.42857); OOP (0.37143); REST (0.37143); Learning (0.37143); Design (0.37143); Docker (0.34286); Databases (0.28571); DBMS (0.28571); JPA (0.28571); Java SE (0.25714); API (0.25714); ORM (0.25714); Linux (0.22857); Kafka (0.22857); Java EE (0.22857); MySQL (0.22857); Hibernate ORM (0.22857); Gradle (0.22857) **(25)**

PHP (1); Git (0.725); JavaScript (0.7); HTML (0.6); CSS (0.6); MySQL (0.6); SQL (0.5); ООП (0.5); REST (0.425); Yii (0.35); API (0.325); React (0.3); Docker (0.3); Design (0.275); jQuery (0.25); Ajax (0.25); Learning (0.25); Laravel (0.225) **(18)**

Swift (0.83333); iOS (0.75); Git (0.66667); Design (0.66667); API (0.58333); REST (0.5); OOP (0.41667); REST API (0.41667); HTTP (0.41667); Responsibility (0.33333); Objective-C (0.33333); iOS SDK (0.33333); Android (0.25); Redmine (0.25); Kotlin (0.25); Scrum (0.25); GitFlow (0.25) **(17)**

Python (1); Git (0.54545); SQL (0.5); PostgreSQL (0.45455); Linux (0.40909); Django Framework (0.36364); Design (0.36364); API (0.27273); C++ (0.22727); OOP (0.22727); Docker (0.22727); Learning (0.22727) **(12)**

C++ (0.73913); C (0.47826); Linux (0.43478); Git (0.3913); C/C++ (0.34783); TCP/IP (0.30435); Learning (0.30435); English (0.26087); Python (0.21739); Windows (0.21739); Testing (0.21739); Micro Controller Units (0.21739) **(12)**

Android (1); Java (0.86667); Kotlin (0.86667); RXJava (0.8); Android SDK (0.6); Git (0.53333); Retrofit (0.53333); Design (0.53333); REST (0.46667); API (0.46667); Responsibility (0.4); ООП (0.4); Teamwork (0.4); SOLID (0.4); MVP (0.4); English (0.33333); Learning (0.33333); Agile (0.33333); HTTP (0.26667); CI/CD (0.26667); MVVM (0.26667) **(21)**

Fig. 5 "Fuzzy" clustering

where *pn* is the number of occurrences of a title in the cluster; *a* is the number of vacancies in the cluster.

Since clusters are built on the basis of skills extracted from vacancies, the following algorithm was implemented:

- skills names within the same cluster are identified;
- skill names are normalized;
- the skill's normal form is searched for in the vacancies of the region; when found, a dictionary with the vacancy code and the name of the vacancy is constructed;
- from the dictionary, built in the previous paragraph, the names of jobs are extracted, excluding the words "Programmer", "Developer", which do not carry information about the vacancy field. Next, the titles are treated as text data. In this case, words that have the same meaning can be written in different ways, such as

"full stack", "full-stack", "fullstack". These discrepancies may occur due to the lack of common spelling and writing conventions for vacancies. Therefore, at the processing step we convert these words to standardize them;
- from the processed vacancies titles a dictionary is formed with the processed vacancy title and the number of occurrences of the given title among all the titles. There are vacancies such as "C/C ++ Programmer" and "C Programmer". A person skilled for the first job can also be a specialist for the second job, but a full name comparison will not provide this information. For this reason, an algorithm for comparing job titles was implemented. The shortest job title is chosen in the pair and the occurrence of the short title in the long one is checked. If the long name has a short one, it is considered that another occurrence is added for the short one. Thus, when comparing the titles "C/C ++ Programmer" and "C Programmer", two occurrences are considered for the title "C Programmer";
- the last step is to find the most popular name with the maximum number of occurrences. This number is divided by the length of the dictionary. Thus, we get the coefficient, which allows us to evaluate the quality of the dictionary.

The results of some evaluations are presented in Table 2.

The table shows the results for different clusters of one region, for different monitoring dates of one region, and for different regions of one monitoring date. From the results, we can conclude that clustering works quite well for the 1C, a specific programming area in Russia. For more widespread skills the evaluation becomes worse. Also in the process of evaluating a challenge was discovered. The clusters dedicated to web programming were characterized by two frequent titles, "web" and "frontend". In terms of skill hierarchy, "web" includes "frontend", and all web occurrences could be summarized into frontend occurrences. However, the developed algorithm takes into account only the symbolic correspondence of the names. As a result, the score for this cluster is low, because the two names close semantically do not have a symbolic similarity.

The quality of clustering was also assessed using expert evaluation [21]. The studied domain requires highly specialized knowledge in the IT field. Therefore, the survey involved employees of the IT companies and professors of the Department of Information Technologies and Computer-Aided Systems of Perm National Research Polytechnic University. Each respondent was invited to evaluate a set of clusters. The form of cluster representation corresponds to Fig. 6.

Table 2 Vacancies titles-based quality evaluation

Region	Monitoring date	The most popular job title in the cluster	Coefficient
Perm Krai	20–08-05	1c	0.915
Perm Krai	20–08-05	Android	0.735
Perm Krai	20–04-05	Java	0.607
Krasnodar Krai	20–04-05	1c	0.910

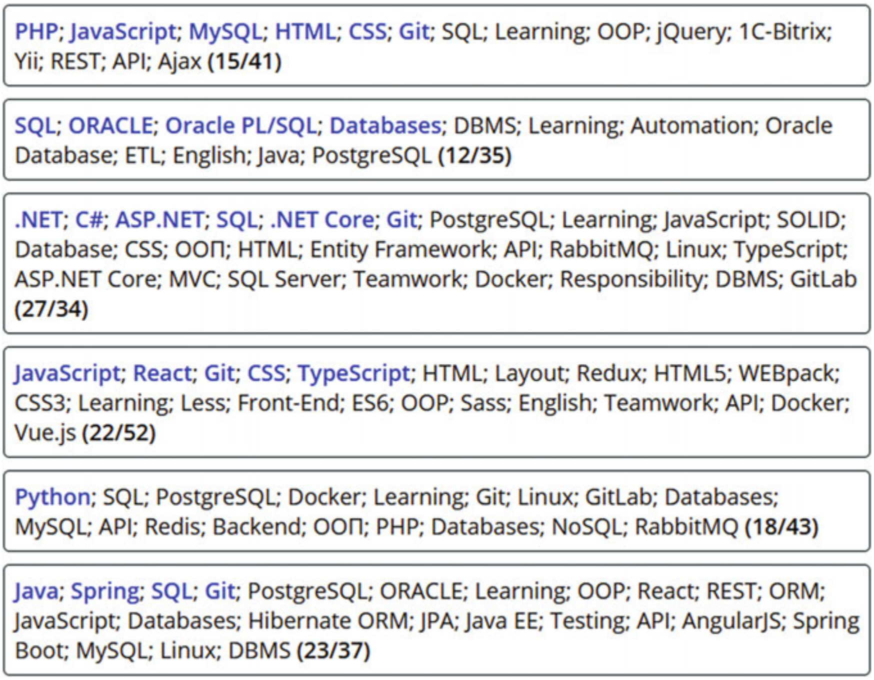

Fig. 6 Cluster output format example

Respondents' age ranges from 23 to 51 years. The work experience in the IT field ranges between 1 and 15 years. Respondents were asked to evaluate the overall quality of groups as a set of programmers' workloads. In this case, the information about the region of data collection and weighting coefficients was not known to the respondents. Information was given about the color indication of the skills that were the most relevant to the cluster. Twenty clusters of different regions and monitoring dates were evaluated. Each cluster was evaluated by at least two respondents. The aggregated average quality score of the clusters is 8.41, which shows the high quality of the clusters formed.

Respondents were also asked the following question for each cluster: "What would you call a specialist with this set of competencies, or what name would you assign to this group?" For example, for cluster 6 in Fig. 6, respondents identified the specialist as "Java Backend Developer". This response was compared to the automated algorithm for selecting a field from a job title. For this region and monitoring date, the "Java" title coefficient for this cluster was 0.91. Examining the skills in cluster 6, we can see the predominance of competencies related to the programming language "Java", which indicates the correct formation of the cluster and the correct evaluation by the respondents.

Respondents labeled cluster 1 as a "Web-backend developer". However, the title allocation algorithm identified "Web" as the most popular name. So, the expert opinion provided a more precise programming field. Examining the skills in the cluster we identified programming languages, technologies, and standards used by web programmers. Thus, the correlation between expert opinion and evaluation based on the developed algorithm was noted.

The aggregated evaluation allowed us to determine the results of clustering as qualitative and relevant to the labor market situation. The proposed clustering algorithm is to be used in the prototype application.

6 Conclusion

The chapter discusses the problem of personnel shortages in the IT field. It proposes a model for identifying and structuring a set of workloads for programmers. It describes the algorithm of the automated vacancies collection, skills extraction, and cluster analysis application as a tool for forming groups of IT specialist workloads. Different types of vectorization were reviewed in this work and the most suitable one for the domain was found through experiments. A quality evaluation algorithm for vacancy-based clustering was developed and an expert evaluation of clustering quality was conducted. The results obtained can be used to create a model of a specialist, that can be used as the basis for a decision support system. The system can increase the efficiency of training and retraining of IT specialists through planning and selection of skills. The implementation of the model may reduce the discrepancy between the specialist's skills and the employer's demands, thus increasing the applicants' employment probability.

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Analyzing of User Actions for the Business Process Models Mining and Automated Building of the Knowledge Base of a Company

M. V. Vinogradova and A. S. Larionov

Abstract The problem to be solved relates to the business process modeling based on the information about user actions to automatically populate the knowledge base of the enterprise information system. The approaches to business process descriptions in the context of various knowledge base models are considered. The model of user work activity based on colored Petri nets is proposed. Methods for the generation of such models based on the knowledge base data using finite state machines have been developed. The finite automata themselves have been created on the basis of human-readable materials of the knowledge base. For this purpose, human-readable materials must be marked up as scripts in the Gherkin language, which is used in the behavior-driven development methodology. These Petri nets models are a reference description of the correct business processes according to experts. They can be used to verify the correctness of user actions in real practice by comparing with the Petri nets models obtained by analyzing the logs of the main information system. As a result, experts have been provided with an interface and software tools to automate the building of the knowledge base of a company. The proposed methods and models increase the efficiency of the enterprise information system application.

Keywords Knowledge management · Enterprise knowledge base · Business processes · Semantic networks · Finite state machines · Petri nets · Sequence analysis

1 Introduction

An enterprise knowledge base is an important tool for accumulating knowledge and professional skills of employees within the enterprise [1]. Acting as a superstructure over the main enterprise information system, it improves the efficiency of the enterprise and provides overall cost savings [2]. An ongoing issue in creating knowledge bases for large and rapidly changing information systems are labor costs to keep

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them up to date. The working hours required to describe the subject area simultaneously and completely can be comparable with the main activity of the enterprise [3]. Methods and tools are required to determine which system elements must be described first and how much in detail, as well as to provide additional information to the author populating the knowledge base.

This chapter describes one of the elements of an integrated approach to creating the enterprise knowledge base, aimed at saving the efforts of the experts populating it and providing users with the most useful information. In our previous work [4], a method for determining priority data and a method for assessing the reduction in labor costs for the knowledge base population were proposed. This chapter proposes a model for describing business processes by experts/compilers and methods for analyzing the correctness of the execution of these business processes by system users.

The object of this chapter is to create an approach to describing the enterprise business processes that allow them to be described in a readable form for users and at the same time to create a model for algorithmic verification of the business process execution correctness in the main enterprise information system.

To reach this objective it is necessary to solve the following problems:

- consider approaches to describing enterprise business processes in various knowledge base models;
- describe the knowledge base model relying on the previously proposed approach to accounting and analysis of elementary user actions;
- develop an approach to the formal description of business processes by experts in a human-readable form, the results of which can be used for the algorithmic analysis of user actions using finite state machine models and Petri nets;
- propose a method for analyzing the business process execution correctness in the main enterprise information system by analyzing the sequences of user actions and creating Petri nets on their basis.

The proposed models and methods facilitate the work of experts populating the knowledge base and provide a better quality of data compilation for it. Methods based on Petri nets are actively used both for modeling the operation of the manufacturing systems themselves [5] and for analyzing the knowledge base rule correctness [6]. The novelty of the approach under consideration lies in the ability for experts to simultaneously create human-readable data for the knowledge base and tools for algorithmic analysis of the real user interactions with the main enterprise information system.

2 Description of the Enterprise Knowledge Base Model

The existing approaches to creating knowledge bases are very diverse, but they can be divided into two families. Those related to the first describe what objects and concepts the considered subject area consists of. The approaches from the second family describe the regularities of the subject area's functioning. In turn, to solve specific problems, each of the approaches is often modified, for example, by adding fuzzy logic or applying hybrid models. As a model that combines the approaches of both families, the MIVAR technology can be mentioned [7].

Approaches describing objects and concepts of the subject area can be called ontological. The most common of these is the description of knowledge bases using semantic networks or frame-based models.

A semantic network model is a knowledge representation system that describes the subject area in the form of an oriented graph, the nodes of which correspond to concepts and objects, and the arcs correspond to the relations between concepts and objects [8]. The most important relations for the inference of new knowledge are the relations of inclusion or coincidence and the "whole-part" relation. Graph nodes describing particular concepts inherit the properties of more general categories, which allows getting additional information about them. The queries to the knowledge base are presented as a fragment of the semantic network using the same node names of relations as in the main network. By searching through the graph, it is possible to identify the truth of the statement in the request or to compile a list of nodes that match the condition.

A frame-based model is a knowledge representation system that describes a subject area as a set of interconnected frames [9]. A frame is a structure for describing a subject area concept, where the meaningful attributes of this concept and their values form an ordered structure of slots. The slot name corresponds to a particular type of attribute, and the slot value can be an instance of this attribute or a link to another frame. Queries to the knowledge base and the inference mechanism are based on the exchange of values between the slots of the same name in different frames and the execution of the "if-added", "if-removed" and "if-needed" procedures attached to the slots.

The approaches describing the regularities of the subject area most often use logical or production models to describe knowledge bases.

A logical (predicate) model is a knowledge representation system that uses a formal language [10]. The words of the language are divided into terms describing the concepts of the subject area under consideration with their properties, and predicates describing the relations between the terms and taking on the values "true", if this relation exists, or "false" if it is absent. Depending on the predicate language level, different quantifiers are also used to limit the predicate truth areas. The inference of new knowledge is the process of obtaining a new formula from a set of known predicate formulas by applying one or more rules of inference. The simplest inference method uses only one rule of inference called resolution. A query to the knowledge base is built as a postulation of one or several relations and their truth test by contradiction.

A production model is a knowledge representation system that describes the regularities of the subject area using the "condition → reaction" rules [11]. A condition is understood as a certain fact known to the knowledge base, and a reaction is a set of actions performed upon its detection. Mathematically, production rules can be described by an ordered triple of sets (1):

$$P = \langle C, A, D\rangle, \tag{1}$$

where C — the condition of the rule; A — the set of facts added by the rule; D — the set of facts removed by the rule.

What production systems have in common is that they consist of three basic elements: a set of rules; a working memory, where known facts and inference results are stored; an inference engine that uses rules according to the contents of working memory. As for the predicate model, direct and backward inference of new knowledge and various methods of resolving contradictions in the rules are possible. A query to the knowledge base is built as a sequential backward rule check, allowing to test the truth of the set of facts that users are interested in.

The primary task of the enterprise knowledge base is to provide ordinary users with reference information in a convenient form. Knowledge bases based on the regularities of the subject area are likely to contain contradictions in their rules if the number of described objects is large enough. This makes it difficult to use them to describe large knowledge bases. Therefore, we turned to creating a knowledge base of an ontological type. The business processes and objects that we plan to document have static sets of attributes, but various relations between elements that are difficult to generalize into a limited number of object types. This makes semantic networks preferable to the frame-based model in terms of clearness.

In the previous paper [4], an approach to creating a knowledge base of a manufacturing enterprise was considered, where objects are grouped according to the most frequent types of user requests. Then the knowledge base model is represented by the following pair (2):

$$Q = \langle V, P\rangle, \tag{2}$$

where $V = \mathrm{A} \cup \mathrm{B} \cup \mathrm{C}$—the set of knowledge base entries (data);

$A = \{a_i\}$—the set of entries on program objects of the system (documents, reference books, etc.), each of which consists of a set of information elements: $a_i = \{e^i_j\}$, $e^i_j \in E$;

$B = \{b_i\}$—the set of business process entries, which are described as sequences of actions (scenarios) for transforming information elements: $b_i =< ..., m^i_p, \ldots, m^i_q >, m^i_j : \{e_k\} \rightarrow \{e_l\}$;

$C = \{c_i\}$—the set of materials on user tasks emerging from the intersection of several business processes ($t^S_i \in T^S$), and entries involved in several business processes ($\{t^{NS}_i\} \in T^{NS}$): $c_i = \left\{t^S_i\right\} \cup \{t^{NS}_j\}$.

$P = \{p_{ij}\}$—the set of relations between knowledge base entries of all types: $p_{ij} =< v_i, v_j >, v_i, v_j \in V$.

The described variety of entries form an ontology that allows the combining of information about specific system objects, general concepts of the subject area, and the relations of both.

New entries are added to the knowledge base by experts/compilers. It is assumed that they have deep knowledge in the subject area, the order of business process execution, as well as methods for solving arising emergency situations. On the other hand, experts do not know how the users of the main information system (employees of the enterprise) actually interact with it. The analytical subsystem of the knowledge base is designed specifically to collect and visualize this data.

As an example of the information system, which acts as a foundation for the knowledge base, the products of the 1C: Enterprise software platform [12] are used. These products are designed to automate various areas of enterprise activity. The platform for storing human-readable information in the knowledge base is Semantic MediaWiki [13]. It is a widespread and at the same time powerful tool for storing data organized according to the principle of the semantic network. Thanks to the built-in logging mechanisms, such a combination provides the analytical subsystem with data on the sequences of elementary user interactions with the main system objects (opening screen forms, change document status, etc.) and knowledge base entries. The graph structure of the main system representation in the knowledge base allows simulating the simultaneous interaction of many users with it [14].

Consider the set of elementary user interactions with the main system F, ordered by time. If necessary, we can distinguish the sequences of elementary events separately for each user (i-th user action track), or a system object for a certain period (3):

$$F^i = \{..., f_p^i, ..., f_q^i\}, \quad (3)$$

where p $< q$.

In turn, each elementary interaction with the main information system to perform a certain type of action $d_l^{'} \in D^{'}$, associated with an element $e_l \in E$ at an instant of time t_l and performed by the user $u_l \in U$ can be described as follows (4):

$$f_q^i = \langle t_l, d_l', e_l, u_l \rangle. \quad (4)$$

Since the objects of the knowledge base form a graph structure [15], representing the structure of the main information system, unique subsets of associated elementary event properties $D_{Pi}^{'} \in D^{'}$, $E_{Pi}^{'} \in$ E, $U_{Pi}^{'} \in U^{'}$ can be mapped to each of its material P^i. These subsets turn out to be useful to map user actions with knowledge base objects using algorithmic methods.

When creating the main system based on the 1C: Enterprise platform, the logbook [16] stores information about the types of recorded actions $D^{'}$, the instances of the objects $E^{'}$ with which they are associated, and the time of each event t_l. Knowledge base entries belonging to the set A describe objects (documents, reference books) of the main information system from the set E. Since each elementary interaction f_q^i refers to a particular object of the main information system $e_l \in$ E, it can be directly mapped to the corresponding knowledge base entry $a_l \in A$. The mapping of the events F^i with the entries of the knowledge base B describing business processes is performed using the analytical apparatus of the knowledge base itself.

3 Conversion of a Human-Readable Description of Enterprise Business Processes into a Formal Model

Consider a method for transforming a human-readable description of enterprise business processes into a formal model. Currently, there are several methodologies and languages for describing business processes [17, 18]. Among them, two main approaches should be distinguished: data flow diagrams and workflow diagrams. These approaches are used together to describe business processes at a generalized and detailed level. For the purposes of our work, a detailed description of business process steps is required, therefore, a subset of the knowledge base elements describing them will be drawn up in the workflow diagram format. Business processes written in specialized notations require knowledge base users to understand this notation. Otherwise, experts/compilers will have to double their work creating both specialized notation and human-readable materials. A common disadvantage of existing languages for describing business processes is the complexity of analyzing the created models by algorithmic methods.

To simplify the creation of human-readable materials and provide algorithmic models with input data, it was decided to describe the knowledge base entries from the set B, describing business processes, in the format of the Gherkin language, which syntax is convenient for building finite state machines on their basis. The Gherkin language is a tool for describing information systems according to the "behavior-driven development" methodology [19]. It allows describing the system behavior in the form of partially structured scenarios in natural language. This form of recording human-readable materials allows recording first the parts of business processes most important for users. An example of a short scenario in the Gherkin language is as follows:

Scenario: [Name].
GIVEN [Initial state property $Q_i \in Q$]
    AND [Initial state property $Q_j \in Q$]
WHEN [Event $D_i \in D$]
THEN [End state property $Q_k \in Q$]
    AND [End state property $Q_m \in Q$].
WHEN [Event $D_m \in D$] OR [Event $D_n \in D$]
THEN [End state property $Q_p \in Q$]
    AND [End state property $Q_r \in Q$].

When drafting a scenario in the Gherkin language for an event $D_i \in D$, the expert needs to provide a textual description of the event in the WHEN section and map it to a link to the elementary event type $D_i^{'} \in D^{'}$ from the list of events being recorded in the main information system. If there are several THEN sections in the scenario, it is required to mark the equivalent states. Thus, each knowledge base entry describing a business process in the form of a scenario in the Gherkin language contains information on two levels. First, it provides easy-to-read information for ordinary users, and second, the markup for generating formal models for further analysis.

Consider the mechanism of transforming the scenario S in the Gherkin language into the finite state machine $S^{'}$ represented by the following quintuple (5):

$$S' = \langle V, Q', q_0, F, \delta \rangle, \quad (5)$$

where V—the input alphabet perceived by the finite state machine;

$Q^{'}$—the set of internal states;

q_0—the initial state $q_0 \in Q^{'}$;

F—the set of final states $F \in Q^{'}$;

δ—the transition function.

In the S scenario in the Gherkin language, the events $D_i^{'} \in D^{'}$ denote conditions for the system's transition between states. They can be interpreted in a similar way for the finite state machine $S^{'}$. Earlier we matched the textual descriptions of events $D_i \in D$ with the types of elementary events $D_i^{'} \in D^{'}$ from the main information system. In this case, the input alphabet V of the finite state machine $S^{'}$ turns out to be similar to the set of events $D^{'}$ being recorded.

The textual descriptions of the system states from the GIVEN and THEN sections are directly translated into the set of internal states $Q^{'}$ of the finite state machine. Each GIVEN and THEN section corresponds to its own internal state $q_j \in Q^{'}$, unless the expert has directly indicated that it is equivalent to $q_i \in Q^{'}$, which was described earlier. The GIVEN section is usually the only one in the scenario and is mapped to the initial state $q_0 \in Q^{'}$. The set of THEN sections with no WHEN sections after them form the set of final states $F \in Q^{'}$.

After transforming the sections of the scenario S into internal states and the input alphabet of the finite state machine $S^{'}$, the transition function δ is automatically generated based on the section sequence. The previous section GIVEN or THEN determines the initial state $q_m \in Q^{'}$, and the subsequent section determines the final state $q_n \in Q^{'}$. The type of the elementary event $D_i^{'} \in D^{'}$ specified in the WHEN section becomes the control character $v_n \in V$ for the transition between the states q_m and q_n.

As a result of such transformations based on the human-readable description of a business process in the knowledge base, one can obtain its formal model in the form of a finite state machine suitable for further algorithmic analysis.

To create a Petri net based on a finite state machine, an algorithm was developed based on the method from [20], which showed that any finite state machine can be transformed into a secure non-redundant Petri net, whose reachability graph coincides with the initial structure of the finite state machine. The structure of business processes described by the experts/compilers is a model of their correct execution in the knowledge base. The Petri net model derived from them will be required at the next stage to verify the correctness of the ordinary user actions. It should also be noted that the description of a business process in the form of a Petri net allows analyzing the reachability of its states and the possibility of further minimizing the structure.

4 Analysis of the Business Process Execution Correctness Using Petri Net Modeling

After obtaining the exemplary models of business processes, they can be used to verify the correctness of user actions in real practice. For this purpose, it is necessary to compare the Petri nets models compiled by experts with the models obtained by analyzing the logs of the main information system. The paper [21] describes a method for generating a Petri net model directly from a set of events ordered in time.

In our case, we have a set of data about elementary interactions of a set of users with the main information system $F^i = \left\{..., f_p^i, ..., f_q^i\right\}$, where p $< q$. As noted earlier, for each of them the instant of time t_l, the type of action $d_i^{'} \in D^{'}$, the instance of the associated element of the main information system $e_l \in E$, and the user who performed it $v_l \in V$ (5) are known.

To create a Petri net model, information is required about the type of each action $d_i^{'} \in D^{'}$ and their time sequence. However, for its structure to be relevant, a subset of events $F_n \in F^i$, constrained by the period and the property types of its constituent elements must be pre-selected by the expert analyst. The 1C: Enterprise platform allows the creation of a convenient interface for selecting elements of a subset and their subsequent uploading to the knowledge base for processing.

Consider the algorithm for generating a Petri net based on the event subset F_n. The Petri net is represented by the following quadruple (6):

$$\mathrm{C} = \langle \mathrm{P}, \mathrm{T}, \mathrm{I}, \mathrm{O} \rangle, \tag{6}$$

where $P = \{p_1, p_2, ..., p_{n-1}, p_n\}$—the finite set of positions, n ≥ 0;

$T = \{t_1, t_2, ..., t_{k-1}, t_k\}$—the finite set of transitions, k ≥ 0;

$I : \mathrm{T} \rightarrow P^*$—the input function—mapping from transitions to position sets;

$O : P^* \rightarrow \mathrm{T}$—output function—mapping from position sets to transitions;

The first step in analyzing the event set F_n is to construct a frequency table that shows the probability of consecution of individual types of events $d_i^{'} \in D^{'}$ and their sequences one after another. If the set F_n contains events of the single business process passage by one user, then the set of non-zero transition frequencies directly specify the sequence of his actions. If within the set F_n there are events from several instances of one business process or events from different business processes, additional analysis is required to distinguish separate competing event streams and information noise.

In turn, within each stream, it is required to distinguish causally related events. An indication of the relation between events $A \in F_n$ and $B \in F_n$ is the case when the sum of the probabilities P of their successive occurrences exceeds a certain threshold Z (7):

$$P = P(AB) + P(BA) > Z. \quad (7)$$

The next step of the analysis is to calculate the entropy $E(S)$ for each event sequence S. If the sequence BA is always followed by the event C, then $E(BA) = 0$ and, in the opposite case, if the sequence BA can be followed with equal probability by any event from the set F_n, then $E(BA) = 1$. The maximum allowable values of entropy $EntLim(N)$ are useful for finding the event stream splitting into N branches. If the total number of possible event types is Q, then the entropy limit values are determined by the following Eq. (8):

$$EntLim(N) = log_Q(N). \quad (8)$$

The closer the entropy value is to the limit value, the more likely it is that the sequence splits into several branches.

The events of the set F_n form the set of transitions T of the Petri net C being generated. Once causal sequences are identified for the events of the set F_n and the branches are defined, the position $p_i \in P$ should be inserted between each pair of consecutive events. Together they form the position set P of Petri net C. As a result of defining the structure of sets T and C, we obtain a set of input functions I and output functions O of Petri net C. Thus, as a result of analysis of the event set F_n, a completed Petri net model is formed, based on the log records about users' actions.

Next, the structure of the resulting Petri net should be compared with the reference model developed on the basis of business-process descriptions done by experts/compilers. The main methods for verifying the user action correctness are a visual comparison of the networks' structure and step-by-step mapping of the business process instances, performed by the specific users. If the sequence of changes in the state of the reference Petri net differs from that obtained by analysis of users' actions, then there are errors in their practical activities.

5 Conclusion

The approach to the description and analysis of business processes outlined in the chapter develops the concept of an enterprise knowledge base proposed by the authors [4]. Entries in the knowledge base are stored in an easy-to-read by users form and at the same time include metadata sets that allow their analysis by algorithmic methods. Human-readable materials are stored using canned software tools, and special tools are required to work with metadata. These tools solve three interrelated tasks: collecting and storing records of elementary user interactions with objects of the main information system, automated algorithmic analysis of these records, and interaction with an expert through a specialized interface.

The description of business processes in the knowledge base in the Gherkin language and their simultaneous partitioning by types of related events in the main information system allows to automatically convert human-readable materials into a formal finite-state machine model, and then into a Petri net. The formal model created in this way is the standard for describing the correct execution of business processes. The 1C: Enterprise software platform provides the ability to log the set of elementary user interactions with the main enterprise information system. The analysis of these interactions makes it possible to create a Petri net model that reflects the actual employee work practice. The comparison of the structure of formal models built by experts and generated by analyzing user actions allows to identification errors in the business process execution.

The proposed models and methods can significantly reduce the labor costs of experts/compilers by automating the business process models' creation and analysis. A promising direction for obtaining information about users' problems is the analysis of their interaction with the graphical interface of the automated information system of the enterprise [22].

Further development of the proposed approach to data analysis makes it possible not only to process the results already obtained but also to use the accumulated data on user actions to predict possible risks in the enterprise operation. The methodology of such an analysis, using a graph data structure and Petri nets, is presented in [23]. Having determined the structure of possible risks at the enterprise level, a similar method can be also used in our case (Fig. 1).

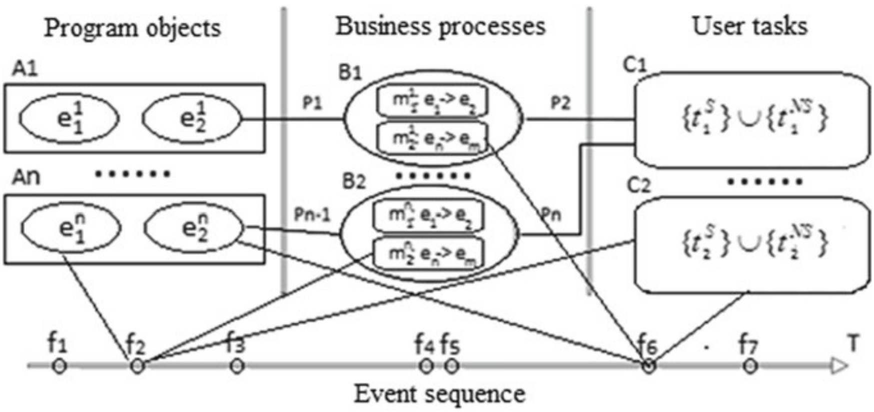

Fig. 1 Illustration of the knowledge base model and its relationship with users' action tracks

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Decision Support System for Fire Alarm Design

Tatiana Shulga and Yuliya Nikulina

Abstract The chapter formalizes the task of designing automatic fire alarm systems under the regulatory documents in force in the Russian Federation. The main directions of the development of fire-prevention regulation in construction are analyzed. The use of cyber-physical systems in the design of fire automation systems has been substantiated. The system analysis of the design process of automatic fire alarm systems and reengineering of the OWL ontology "Systems of fire protection" previously created by the authors has been carried out. The advantages of using the ontological data model over databases when solving the problem under consideration are substantiated. An example of the application of axioms existing in ontology for solving practical problems is given. The part of the ontology that was designed to solve the problem of categorizing a room by explosion and fire hazard has been filled in. The RDF dataset developed based on the ontology is placed in the public domain and can be used in the development of any applications in the field of fire safety. The algorithm for deciding on fire has been formalized. The structure of the decision support system to design fire protection systems is proposed. The knowledge base of the system is developed based on the ontological model proposed by the authors. This DSS can be used by organizations involved in the design, installation, and maintenance of fire protection systems. A module of the decision support system has been developed to determine the category of premises for a fire hazard.

Keywords System analysis · OWL-ontology · A system of fire protection · Fire alarm system · Cyber-physical system · Fire detector

1 Introduction

Every year, at the state level, more and more attention is paid to the issue of ensuring fire safety. In March 2021, several new sets of rules came into force, regulating the rules and regulations for the design of fire protection systems.

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Also, from 2022, the use of building information modeling (BIM) technologies will be mandatory for all government orders financed from the budget of the Russian Federation, that is, all contracts concluded after January 1, 2022, for the construction of schools, hospitals, kindergartens, and other facilities, financed at the state expense, must contain provisions on the formation and use of the BIM-model. Thus, it will become mandatory to use cyber-physical systems in construction, including in the design of fire protection systems. Experts believe [1, 2] that subsequently the design of all objects will be carried out using cyber-physical systems, therefore, organizations operating in this area need to start rebuilding their business processes and introduce BIM into their activities. The advantages of using cyber-physical systems for solving fire protection problems are improving the efficiency of processes in the process of continuous exchange of information, during which monitoring, control, and management of systems are carried out, as well as increasing the efficiency of resource management by optimizing the operation of applications with taking into account the current situation [3].

In recent years, a large number of scientific works (for example, [3–5]) have been devoted to solving the problems of developing models and methods for supporting decision-making to prevent fire hazardous situations at enterprises. But in these studies, due attention is not paid to solving the issues of designing fire protection systems for objects. In addition, the implementation of existing software products designed to solve this problem in Russian design organizations causes some difficulties [6], associated primarily with the lack of an integrated system of regulatory and legal documentation and the need to retrain personnel and rebuild the organization's business processes to work with foreign products not adapted for Russian conditions.

In this work, a systematic analysis of the process of designing fire alarm systems and formalization of the solution to this problem is carried out. These results are used by the authors to create a DSS used in the design of fire protection systems. It is assumed that the knowledge base of such a system will be developed based on the ontological model proposed by the authors. It should be noted that the ontological approach has become popular in recent years in the representation of knowledge in various subject areas (for example, [7, 8]) due to the provision of flexibility in the design and modification of models and their openness.

2 System Analysis of the Process of Designing Fire Alarm Systems

The concept of a fire automation system is defined in [9]. It means a set of interacting fire alarm systems, the transmission of fire notifications, warning, and management of evacuation of people, smoke ventilation, automatic fire extinguishing installations, and other automatic fire protection equipment designed to ensure the fire safety of the facility. The main task of the fire automation system is to automate the collection and processing of information, control the executive devices of the fire protection system in automatic and manual modes according to a given algorithm, generate control signals for engineering and technological equipment involved in ensuring the fire safety of the facility.

The term project of a fire protection system (working draft) is not legally defined but is used by specialists in this field to denote a set of materials and documents prepared as a result of the design of such a system. The project of the fire protection system consists of two sections: textual—an explanatory note and graphical—floor-by-floor, consolidated plans-diagrams.

In this chapter, we will focus on the design of a fire alarm system. According to the definition, such a system is understood as a set of interacting technical means designed to detect a fire, generate, collect, process, register, and issue in a given form fire signals, system operation modes, other information, and issue (if necessary) initiating signals to control technical fire protection means technological, electrical and other equipment.

After the customer contacts the design organization, the preparatory stage of project development begins, also called the pre-design survey of the protected object. At this time, there is a collection of information from the customer of the project on the architectural solutions of the protected object. There is a choice of basic technical solutions for creating the structure of a fire protection system based on standard solutions, taking into account the specifics of premises, buildings, structures, also according to their functional purpose.

The project architect can draw up a technical assignment for the design of fire protection systems, but if it is absent in real practice, the preparation of the technical assignment can be carried out by the design organization together with the customer, then agreed and approved by him. This is the main document for starting the design, which defines all aspects—from the type of installation system, main technical characteristics to possible modes of operation, integration with the engineering systems of the protected object. The choice of the type of fire detector should be based on the characteristics of the prevailing combustible load and the prevailing fire factor at its initial stage [10].

The next stage is the actual development of project documentation. It begins with drawing up sketch plans, creating a basic structure with an indication of the list of equipment used; schemes for laying alarm loops, connecting, network cable lines, places of installation of fire detectors, sirens.

The calculation of the scope of work and the cost of design depends on the size of buildings, structures, the features of their space-planning solutions, for example, the presence of suspended ceilings, raised floors, the functional purpose of premises, technological processes in them, as well as the category of explosion and fire hazard (the process of determining which is described in detail in [11]), the need to integrate/block the automatic fire alarm installation with utilities (SOUE), warning systems and evacuation control in case of fire, fire pumping stations. The above documents and procedures are reflected in the ontology [10] in the form of classes, properties (Fig. 1), and also axioms (restrictions on the joint use of classes and properties). The ontology was developed in the OWL language.

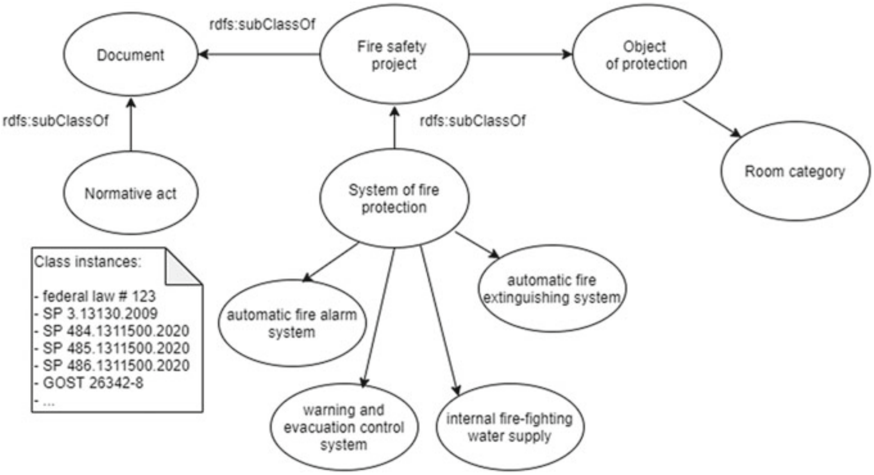

Fig. 1 Fragment of the structure of classes of the ontology "Systems of fire protection"

Data representation using ontologies has several advantages over databases, the main ones being flexibility, openness, and extensibility. In addition, if the ontological model is built using the apparatus of descriptive logic, the axioms of the ontology (in fact, determining the inference rules) allow obtaining new data combinations, while the database schema imposes restrictions on its structure and all admissible data combinations are determined.

Implementation of fire protection measures using the ontological approach is successfully applied in world practice [12–15]. The authors carried out a comparative analysis of existing projects [10]. However, the ontologies considered in this study have some disadvantages and are not suitable for solving the problem posed by us. In particular, they do not contain classes and properties that take into account the nuances of Russian legislation: the existing systems for classifying fire hazard, fire risk, premises designation, etc. in our country.

The automatic fire alarm system (APS) should be designed to fulfill the following main tasks: timely fire detection; reliable fire detection; collection, processing, and presentation of information to the duty personnel; interaction with other (if any) fire protection systems (formation of the necessary initiating control signals), an automated process control system, emergency protection and engineering systems of the facility.

Then the project documentation must pass the state examination. An organization licensed for this type of activity issues instructions and comments. Working documentation is issued based on project documentation. It is she who is used when performing installation and commissioning work. Contains equipment drawings, diagrams of all connections, cable log with the length of all sections of alarm loops, connecting, supply lines; plan diagrams with the arrangement of detectors, annunciators, devices; data on the total amount of materials required for the work. Upon completion of the installation of the system, as-built documentation is prepared, which also includes a graphic part and, if necessary, a textual—explanatory note. The final design stage—preparation of estimate documentation based on the specifications of all devices, fire alarm devices, necessary materials; current prices for equipment, and types of work, which is coordinated, approved with the customer.

The work [10] describes in detail an example of the application of axioms existing in ontology for choosing the type of fire detector (IP) and considers the rules for the location of point fire detectors. The choice of the type of fire detector depends on the purpose of the protected premises and the type of fire load.

An example of obtaining new information using the constraints (axioms) available in the described model is the use of the transitivity of the "has" property: if the protected object A has the type of purpose of the protected room B, and the type of purpose of the protected room B has the form of a fire detector C, then the protected object A has the type of fire detector V.

After the publication [10], the work on the ontology was continued: the classes "Fire alarm control zone (ZKPS)" were added, associated with the class "Protected object" by the "Consists of" property. Also, new copies were added to the regulatory documentation—manuals for the operation of the main components of fire automation systems. Each manufacturer of equipment for fire protection systems has its nuances, they should also be taken into account when designing such a system.

In addition, a part of the ontology was filled, concerning the problem of categorizing the premises by an explosion and fire hazard. It was filled in based on reference information on the fire hazardous properties of substances and materials. The RDF dataset developed based on the ontology contains information about more than one and a half thousand substances and materials (name, molar mass, the density of substances, Antoine's constants, etc.). Based on these values, the room category is calculated.

The developed dataset is placed in the public domain and can be used in the development of any applications in the field of fire safety [16].

The developed ontology was placed on the Apache Fuseki server for its further use in the DSS module "Definition of the category of premises by fire hazard", as well as interconnection with other modules of the developed application.

3 Formalization of the Problem of Deciding by the System About Fire

One of the important functions of the fire alarm system is to make a decision on fire and launch all provided systems—warning and evacuation systems in case of fire (SOUE) and launching an automatic fire extinguishing installation (AUPT). In practice, when designing such a system, the determination of the number of sensors in a room depends on the chosen algorithm. The choice of a specific algorithm is carried out by the design organization. Therefore, we were also faced with the task

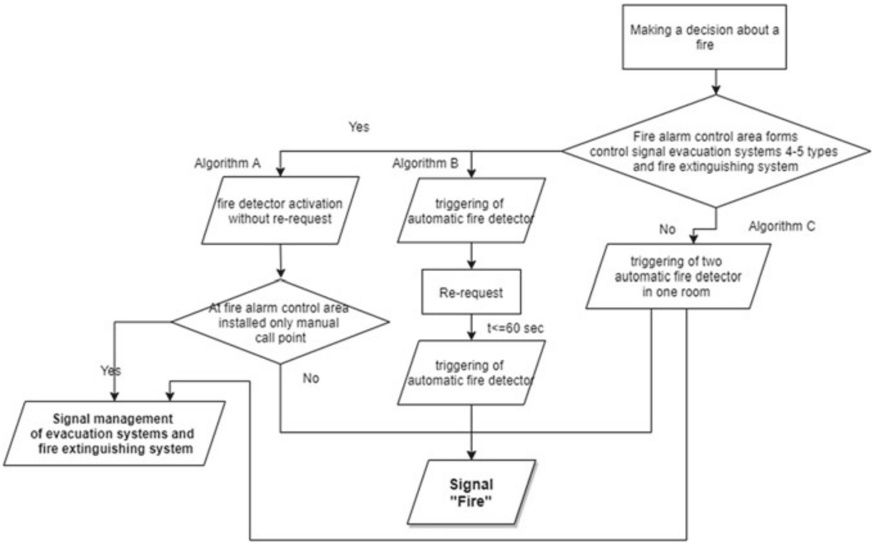

Fig. 2 The algorithm for deciding on fire

of formalizing this process. Let us formalize the algorithm for making a decision by the system about fire and launching all envisaged systems [9]. Decision-making on the occurrence of a fire in a given fire alarm control zone, according to regulatory documents, should be carried out by performing one of the algorithms: A, B, or C (Fig. 2). It is allowed to use different algorithms for different parts (rooms) of an object. The choice of a specific algorithm is carried out by the design organization.

The algorithm is recorded with the help of special software on the monitoring and control panel of the security fireman, which, during operation, monitors and controls the state of the protected object. Together with other elements of fire protection, it performs the functions of a block-modular device for receiving and monitoring security and firefighters, a control device for light, sound, and voice alarms, gas, powder aerosol, and water fire extinguishing, smoke protection, and building engineering systems, including systems involved in providing fire safety.

4 Development of a Decision Support System for Solving the Task

The authors proposed the structure of the decision support system (Fig. 3). To determine the necessary functional features of the application, an analysis of the existing software products on the market was carried out. In [17, 18], the successful application of the DSS for the implementation of fire protection is described. The application has an architecture characteristic of a decision support system, contains inference

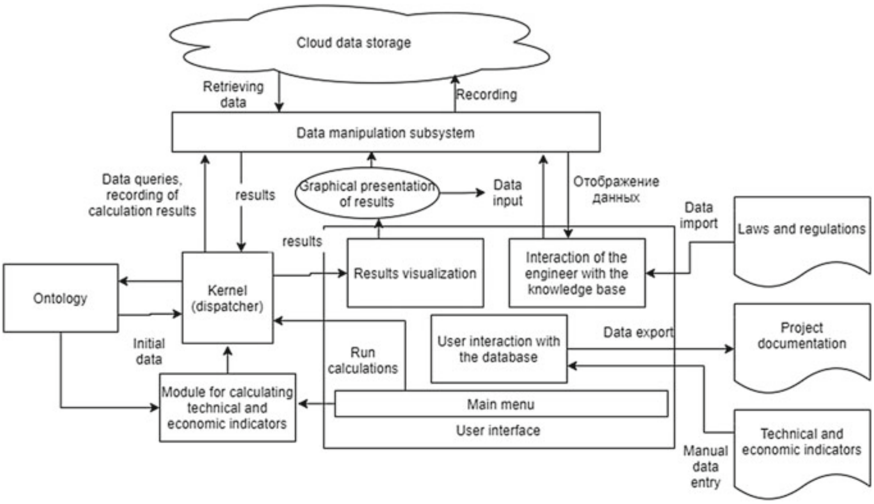

Fig. 3 DSS architecture

rules that automatically display the calculated values of the necessary technical and economic indicators. The properties and axioms described in the ontology allow a logical conclusion. The decision support system is based on the obtained data model, the result of which is a fragment of the project of the fire safety system necessary for each protected object—the category of the room is determined by an explosion and fire hazard. Calculations and reference data necessary for making calculations are also displayed.

The software market today offers a fairly limited number of solutions, most of which are of foreign production. The cost of foreign programs is high, moreover, they require adaptation to our standards. There are also domestic developments. Their cost relative to foreign counterparts is lower, but since they were developed not so long ago, these programs have several shortcomings and shortcomings. Of the domestic developments, the most common is design automation systems that work in conjunction with AutoCAD and NanoCAD programs. NanoCAD is a graphical editor of domestic production, made by analogy with AutoCAD. A comparative analysis showed that the introduction of such software products causes some difficulties, the main of which is the lack of an integrated system of regulatory documents and the need to retrain personnel and restructuring of the organization's business processes to work with foreign products that are not adapted for Russian conditions [19], they also have quite a high cost, and thus not suitable for small and medium enterprises.

Thus, the task was set to create a software product that combines both the capabilities of Business Intelligence tools and the ease of use of the interface and affordability in terms of price and development costs. Such projects are launched by foreign researchers and show their effectiveness, but it is not possible to apply them due to the specifics of legislative norms [20, 21].

Based on the analysis of existing software products, the functionality necessary for such an application was determined: import of data presented in several common formats; preliminary data processing; building a model; the ability to automatically select a forecasting model; calculation of forecast values for future periods; visualization of forecasts, which includes the construction of a graph of forecast values; export of the obtained results to a file. The structure of the system should provide for the possibility of expanding the functions performed, as well as the modernization of existing algorithms. Existing DSSs using cyber-physical systems have similar features [22, 23]. For example, the results of continuous monitoring obtained with the help of fire control systems can be used, for example, to obtain information about the state of the premises during an emergency [24, 25].

However, the proposed DSS has two distinctive features:

- application of an ontological approach that ensures the extensibility of the system,
- the presence of an integrated system of regulatory documents of the Russian Federation in the domain of fair protection (as part of the ontological knowledge base), which ensures a reduction in the development time of projects.

5 Conclusion

Thus, the main directions of development of fire-prevention regulation in construction have been analyzed and the task of designing fire alarm systems has been formalized. The results of the work were used in the design of the DSS for organizations engaged in the design, installation, and maintenance of fire protection systems. This kind of DSS can be considered in the future as an element of a cyber-physical system for creating projects of fire automation systems, carrying out continuous control and monitoring, as well as timely maintenance. At the moment, a DSS module has been developed to determine the category of premises for fire hazards, which is undergoing the state registration procedure as a computer program. In the future, it is planned to develop and implement the DSSS methods for choosing the most economically profitable configuration of the project of a fire protection system, taking into account the restrictions determined by regulatory documents.

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